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This report describes the research undertaken by the Center of Excellence in Theoretical Geoplasma Research which was established at MIT in 1986 through a contract from the Air Force Office of Scientific Research (F49620-86C-0128) under the University Research Initiative (URI) program.

In the course of this research effort, members of the center have contributed to a number of definitive research findings in the fundamental understanding of ionospheric turbulence, particle acceleration, and the phenomena of coupling between the ionosphere and magnetosphere.

A majority of these research programs have benefited from a vigorous visiting scientists program involving active collaborations among members of our center and established experimentalists and theoreticians from various research laboratories and

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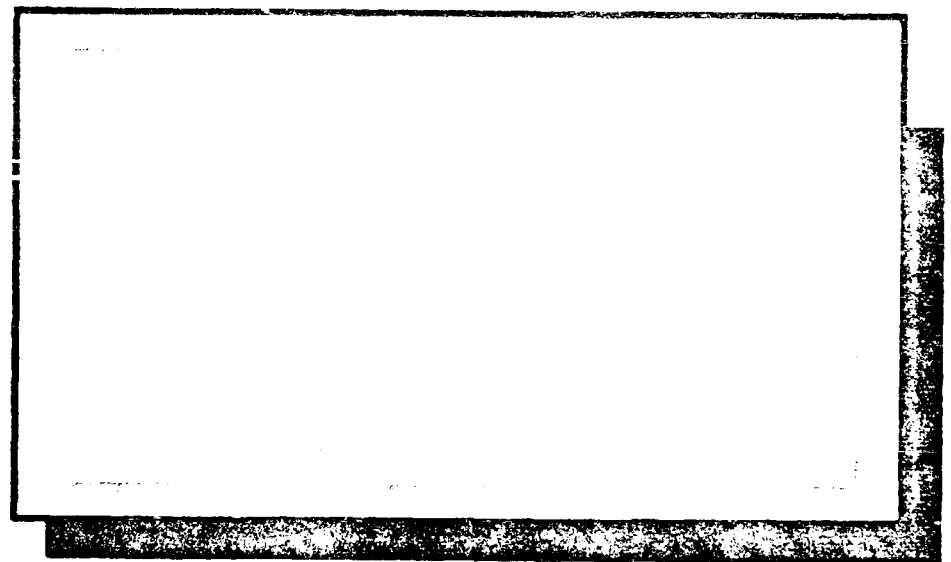
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universities including the Air Force Geophysics Laboratory and our sister AFOSR/URI institute, the Utah State University. In addition, a number of our research findings have already found practical applications by our colleagues at or affiliated with the Air Force Geophysics Laboratory.

We have established an annual Cambridge Workshop which draws scientists and students from around the world to MIT in order to discuss specific current topics of geoplasma physics. These summer workshops and the MIT Winter Symposia on the Physics of Space Plasmas have firmly established MIT as a cornerstone in geoplasma research and education.

In short, we have developed and are maintaining a program of excellence in both basic research and graduate education in geoplasma physics in support of the primary mission of the Air Force.

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CENTER FOR SPACE RESEARCH  
MASSACHUSETTS INSTITUTE OF TECHNOLOGY



A Final Report Submitted to the  
Air Force Office of Scientific Research  
describing Research under the URI topic

**Theory & Analysis of the  
Geo-Plasma Environment**

performed under Contract F49620-86-C-0128  
to the Massachusetts Institute of Technology  
November 10, 1989

A Final Report Submitted to the  
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH  
describing the research of the

**CENTER OF EXCELLENCE IN  
THEORETICAL GEOPLASMA RESEARCH**

performed under Contract F49620-86-C-0128 from the  
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*Theory and Analysis of the Geo-Plasma Environment*

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**I. ABSTRACT**

This report describes the research undertaken by the Center of Excellence in Theoretical Geoplasma Research which was established at MIT in 1986 through a contract from the Air Force Office of Scientific Research (F49620-86C-0128) under the University Research Initiative (URI) program.

In the course of this research effort, members of the center have contributed to a number of definitive research findings in the fundamental understanding of ionospheric turbulence, particle acceleration, and the phenomena of coupling between the ionosphere and magnetosphere.

A majority of these research programs have benefited from a vigorous visiting scientists program involving active collaborations among members of our center and established experimentalists and theoreticians from various research laboratories and universities including the Air Force Geophysics Laboratory and our sister AFOSR/URI institute, the Utah State University. In addition, a number of our research findings have already found practical applications by our colleagues at or affiliated with the Air Force Geophysics Laboratory.

We have established an annual Cambridge Workshop which draws scientists and students from around the world to MIT in order to discuss specific current topics of geoplasma physics. These summer workshops and the MIT Winter Symposia on the Physics of Space Plasmas have firmly established MIT as a cornerstone in geoplasma research and education.

In short, we have developed and are maintaining a program of excellence in both basic research and graduate education in geoplasma physics in support of the primary mission of the Air Force.

## II. INTRODUCTION

Recognizing the need for the basic understanding of the various relevant geoplasma processes that dominate the "weather" in space, a Center of Excellence in Theoretical Geoplasma Research was established at the Massachusetts Institute of Technology in 1986 under the sponsorship of the Air Force Office of Scientific Research (AFOSR) University Research Initiative (URI) program. The goal of the Center was to foster interdisciplinary frontier research and graduate education in the physics and interactions of the Earth's ionosphere and magnetosphere.

During the past three years, our Center has made substantive strides toward the goals set forth in the original 1986 AFOSR-URI proposal. In the research area, we have made considerable progress towards the understanding of several important microscale-mesoscale-global problems encompassing ionospheric-magnetospheric interactions of considerable geoplasma importance. These include the study of the formation of the counterstreaming electrons in the discrete auroral zone, the formation of double layers along auroral field lines, the origin of *high-latitude ionospheric* turbulence and its relevance to charged particle acceleration processes, the development of the anisotropic photoelectron distributions and the associated anomalous heat fluxes in the polar wind ionosphere, the acceleration processes leading to the bowl-shaped oxygen conics in the diffuse auroral and cusp/cleft regions, and relativistic theory of auroral kilometric radiation and related plasma processes. Altogether, we have published forty-seven (47) technical papers and five (5) books, and presented sixty (60) invited and contributed presentations at various national and international conferences.

A number of the aforementioned research findings have already found practical applications by our colleagues at or affiliated with the Air Force Geophysics Laboratory. Examples of such applications are: prediction of charged-particle precipitation patterns and deposition profiles in the diffuse-auroral zone of the ionosphere; prediction of solar EUV and X-ray fluxes based on ionospheric photoelectron measurements and transport calculations; and calculation of ionospheric electron density profiles in the mid-latitude and high-latitude portions of the globe.

The Center has interacted actively with a number of research organizations including the Air Force Geophysics Laboratory, the Naval Research Laboratory, the Southwest Research Institute, the Lockheed Palo Alto Research Laboratory, the Utah State University, Boston College, the National Research Council of Canada, the Swedish Space Institute, the Finnish Meteorological Institute, the Max-Planck Institute for Extraterrestrial Physics, Cornell University, the University of California at Berkeley, the University of California at Irvine, Imperial College, the University of Maryland, and the Taiwan Center for Space and Remote-Sensing Research. Visits by scientists from these and other institutions have provided the necessary stimulus to keep our research program vibrant, up-to-date, and at the same time constantly in touch with the practical motivations.

We are particularly proud of the mutually beneficial collaborations with our sister AFOSR-URI institution, the Utah State University. Research activities at the two institutions, though different in nature and scope, compliment each other. For example, our photoelectron calculations along polar open field lines, compliment nicely the detailed analyses of the polar wind using the moment method developed at Utah State. In addition, Dr. Robert Schunk, Director of the URI program at Utah State has visited us several times and delivered invited lectures at the Cambridge Workshops described below.

We have organized several Winter Symposia on the Physics of Space Plasmas. The principal purpose of these symposia is to provide an annual get-together for representatives from the various research groups, in the Boston-New England area and nationwide, working on problems related to space plasma physics. These symposia have received strong support from the Air Force Geophysics Laboratory and were well attended by scientists from that laboratory and other research and educational institutions. For example, Drs. H. Carlson, J. R. Jasperse, R. Sagalyn, W. Burke, E. Weber, J. Klobuchar, N. Maynard, and S. Ossakow have contributed significantly to these scientific gatherings.

The 1987 symposium included a keynote lecture on the "Plasma Universe" by the Nobel Laureate, Professor Hannes Alfvén of the

Swedish Royal Institute of Technology. Professor Alfvén has embraced the goals of our center with open arms and has lent his name to a new series of prestigious lectures to be sponsored by MIT at its annual winter symposia. Alfvén Lecturers during the 1988 and 1989 symposia included Dr. Roger Gendrin, Director of the French National Laboratory of Ionospheric and Magnetospheric Environmental Physics and Professor James Dungey of Imperial College, London; both are world-renowned for their pioneering work in geoplasma research.

The Center also inaugurated a series of Cambridge Workshops in Geoplasma Research. One of the major difficulties encountered in initiating or pursuing innovative geoplasma activities by researchers and beginning graduate students is the limited number of fundamental accounts of the subject. The Cambridge Workshops were conceived to address such a need. Each workshop is targeted at a specific topic of frontier geoplasma research and accordingly includes basic tutorial talks and invited specialty lectures. Even more specialized discussions have been effectively encouraged with poster presentations. The format of the workshop has been designed to allow ample time for formal and informal discussions and interactions. Each of these workshops and symposia has attracted over one hundred and thirty participants from the US and abroad and included both established scientists and graduate students. These activities have received much praise from the world-wide geoplasma community for their innovative concepts and educational merits. Proceedings of these activities have been published by the Scientific Publishers, Inc. as volumes of its "Physics of Space Plasmas" series and are expected to become informal textbooks dealing with the particular research topics discussed at these gatherings.

The Center is currently composed of twenty-three (23) active members. These include members of the faculty, staff, postdoctoral and graduate students at MIT as well as several visiting scientists from other interacting institutions. Members of our Center have been invited by various conferences, universities and other organizations to deliver invited and review lectures.

Our visiting scientists program continues to flourish and has been expanded to include experimentalists and theoreticians from the US and

abroad. (Among the scientists who are visiting our Center this year are Drs. J. R. Jasperse, J. M. Retterer, and M. Heinemann of the Air Force Geophysics Laboratory.) A number of new research programs have received their impetus from these interactions.

Our computer capability has been greatly enhanced. Through our network of workstations, we are tied to the MIT campus network, the DARPA internet, the NASA SPANnet and nearly all of the electronic mail networks, domestic and world-wide. We continue to have access to the Cyber machine at the Air Force Geophysics Laboratory and have high speed access (1.5 Mbps) to the class VI and VII supercomputers of the John von Neumann Computing Center at Princeton, N.J.

This report is organized as follows. In Section III, we discuss in detail the progress, accomplishments, and major research programs of the Center. This is followed by brief accounts of other relevant Center activities in Section IV. A listing and introduction to the currently affiliated members of the Center is given in Section V. Listings of significant publications and scientific presentations are to be found in Sections VI and VII.

**III. PROGRESS, ACCOMPLISHMENTS, AND MAJOR RESEARCH ACTIVITIES AT THE CENTER**

We proposed a unique program of theoretical research in geoplasma physics in our original 1986 AFOSR-URI proposal. The Center we proposed would be a single cohesive unit of scientists from several disciplines interacting effectively with one another and with groups from external ongoing experimental research programs. It would not be the purpose of the Center to carry out routine data analyses and the like. These tasks were deemed to be more efficiently performed by the in-house analysts of the experimental groups. Instead, our proposed approach would be to interact with the experimental groups, to identify from the analyzed data those problems which had no ready-made or adequate physical explanations, and to focus effort on the solution of such new problems by efficiently utilizing the interdisciplinary nature of the Center. Thus our task would be to appreciate, to absorb, to delineate, and finally to understand these ever-present new problems. We recognized that an understanding of the basic physics of these problems would require a thorough appreciation of the surrounding circumstances associated with the basic phenomena. From this, we could proceed to make rough formulations describing the physics, to test out these formulations analytically, numerically or via plasma simulations, and finally to extract from these initial efforts the true underlying physics and to construct more realistic physical models for further theoretical analyses. At all times, we would not lose sight of the original physical problems motivating the analyses, nor the practical applications of the developed theories to the prime mission of the Air Force.

Throughout this effort, we would try to avoid doing theoretical analyses for the sake of the theory itself. It was also to be our philosophy that numerical tools should be addressed to the problems of interest, rather than working on the "latest" codes and then groping for problems amenable to their application. Another consideration was that the geoplasma environment is much too complicated to allow pure analytical studies which do not seek the guidance of the experimental results obtained from space or simulated in the laboratory.

*In the past three years, we have endeavored to follow such guidelines while developing the various research programs at the Center. We believe that we have succeeded in every aspect of the above goals while pursuing our research activities. We feel that we have identified many new, interesting, and at the same time puzzling geoplasma problems which were not admissible to "routine" solutions. We have provided theoretical understandings to a number of such problems. In many of these instances, we were able to provide quantitative descriptions of the phenomena or were able to make useful theoretical predictions for future observations.*

For example, our understanding of pitch-angle scattering and the dynamics of the central plasma sheet allowed us to construct a quantitative model of electron precipitation in the diffuse aurora. Because this precipitation helps control the electron density profile in the high-latitude ionosphere, it has a strong impact on the Air Force communication and surveillance systems that must operate in the region. Similarly, because of the effect of scintillation on these systems and the close relationship between scintillations and the high-latitude ionospheric plasma turbulence, our quantitative models of the latter phenomena and its consequences (models already developed or being developed) can be expected to have great utility in the practical business of ionospheric weather prediction.

Throughout the remainder of this Section, we shall attempt to outline the progress, accomplishments, and major activities of some of the most important research activities of the Center.

### III.A. Transverse Acceleration and Heating of Ionospheric Ions and the Formation of Ion Conics

Geoplasma physicists have measured energetic positively charged ionospheric ions at the auroral and polar cusp latitudes. It appears that these ions gyrate around the geomagnetic field lines at extremely high speeds (energies ranging from tens of eV to tens of keV) while flowing upward from the low altitude ionosphere into the magnetosphere. Such populations of these ions have been christened "ion conics". The term "conic" refers to the fact that these ion distributions are strongly peaked in pitch angle, so that they are concentrated on a cone in velocity space. The discovery of conics was somewhat startling, largely because no mechanism for transversely accelerating ionospheric ions to what are essentially magnetospheric energies had been anticipated. It is probable that these ions were accelerated transversely by the plasma waves that are omnipresent in the turbulent region of the high latitude ionosphere and magnetosphere. Since the geomagnetic field decreases with altitude, as the ions drift to higher altitudes, some of this transverse energy is converted to upwards motion, thereby transforming the "shape" of these distributions into velocity space conics (Fig. 1).

We have contributed some very important theoretical discoveries pertaining to the basic heating mechanisms of this type of ion population and made some definitive strides towards the prediction and calculation of the details of the various types of ion conic distributions in the geoplasma environment. We have been invited by various international conferences and research institutions to lecture on these ideas, including in a review lecture given at the Third International School on Space Simulations held at Beaulieu, France in June 1987 and invited lectures at the Twenty Second General Assembly of the International Union of Radio Science in Tel Aviv, Israel in September 1987, the 1986 Plasma Physics Meeting of the American Physical Society in Baltimore, in November 1987, and the 1988 National Radio Science Meeting in Boulder, Colorado, in January, and the Eringen Symposium of the Society of Engineering and Science at Berkeley, CA in June 1988. Some of these new research results are summarized in the following three sub-sections. We also indicate the direction of our major research activities in this area.



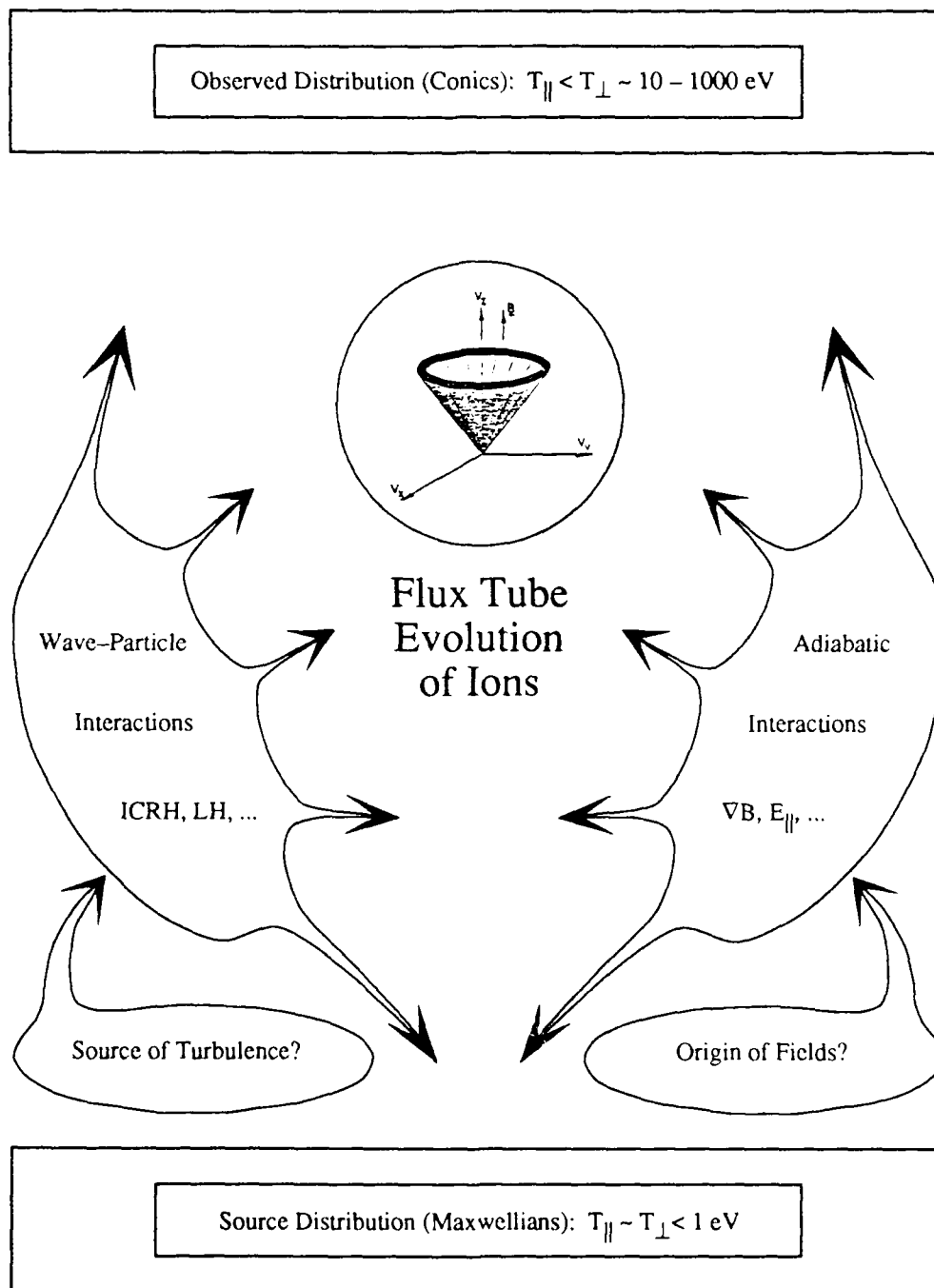


Figure 1. A schematic diagram of the conic formation process whereby low energy ionospheric plasma is energized through wave particle interactions to magnetospheric energetics. The variety of conic formed is determined by both the type of wave turbulence participating, as well as the various adiabatic forces which also may play a role.

*1. Transverse Heating of Ionospheric Ions Along Auroral Field Lines, in the Polar Cusp/Cleft, over the Polar Cap, and in High Velocity Shear Regions by Intense Electromagnetic Turbulence in the Ion Cyclotron Range of Frequencies*

*(a) Ion Heating Along Auroral Field Lines in the Central Plasma Sheet*

As discussed above, the ion conics which have been observed in various regions of the Earth's ionosphere-magnetosphere system is a current research topic of intense theoretical interest. We have made considerable progress in explaining a class of these events along auroral field lines in the central plasma sheet (Fig. 2) through a theory in which the energization of the conics arises through cyclotron resonance with a broad band of electromagnetic waves that are frequently observed in the turbulent region of the high-latitude ionosphere. The nature of this acceleration mechanism is such that it has been possible to make significant analytic progress towards a description of the resulting particle distributions.

We have performed a series of Monte Carlo particle simulations to test the ideas of our theory and to make quantitative comparisons with the observed particle distributions. At each altitude one can

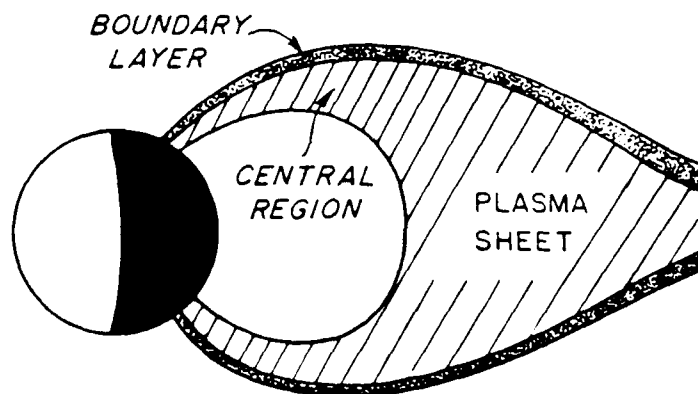


Figure 2. A magnetospheric "cartoon" delineating the major plasma sheet regions.

approximate the effects on the particle distribution through local cyclotron resonance with the observed low frequency turbulence by means of a quasilinear-type velocity space diffusion operator. Since the waves are present over a range of frequencies corresponding to cyclotron frequencies over a range of altitudes in the Earth's bipolar magnetic field, the ions are able to extract energy continuously as they drift up along the geomagnetic field lines. With reasonable assumptions, the Monte Carlo simulation is able to quantitatively trace the evolution of the entire distribution of particles throughout this process, and the agreement with the conics observed in the central plasma sheet by the Dynamics Explorer 1 satellite is dramatic (Fig. 3). *To our knowledge, this represents the first quantitative comparison between any theory of ion acceleration with ion populations observed in space.* Our results were reported in the prestigious journal, Physical Review Letters (59, 148, 1987).

Encouraged by these results, we have pressed our theoretical analysis of this mechanism with a number of goals in mind. These include an enhanced understanding of the process, a sharpening of theoretical tools for their potential application to other problems, and a recognition that while numerical simulations are useful for demonstrating the validity of theoretical notions, they are sorely inadequate for application to the analysis and reduction of sizable data sets. For example, we have identified a scaling which may be used to advantage in reducing the dimensionality of the problem and have reformulated the reduced problem in terms of a Langevin equation. One result of this reformulation is an improved numerical simulation which achieves results similar to the Monte Carlo simulation with an increased efficiency which translates into a reduction by orders of magnitude of the required computer time.

Of equal significance is the fact that this reformulation makes a natural starting point for further theoretical development. In particular, exploiting techniques originally developed in condensed matter and elementary particle physics, we are effectively able to obtain a closed form solution of this quasilinear diffusion problem in terms of a path integral similar to those employed in quantum field theory. Furthermore, the result is amenable to evaluation using Feynman diagrams in order to

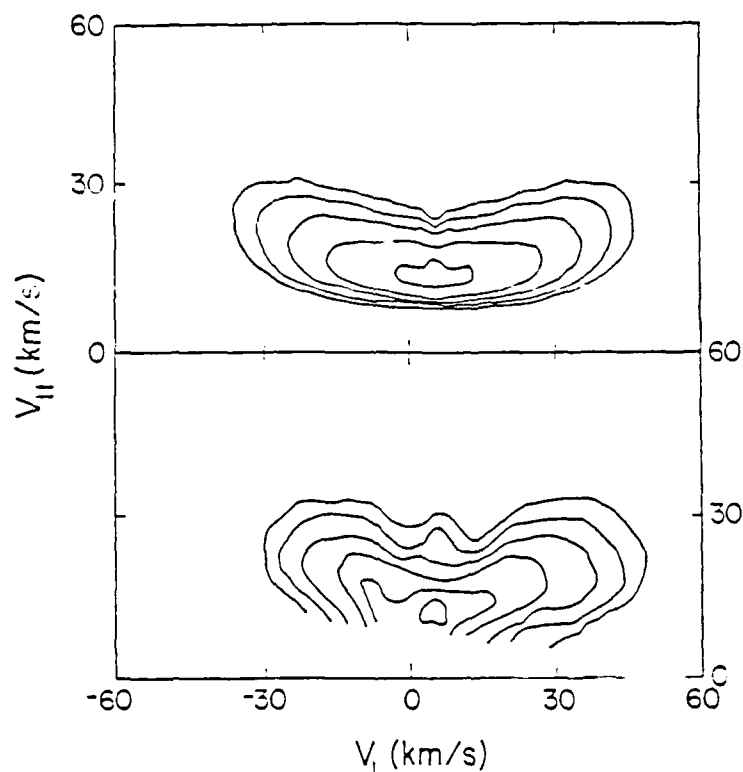


Figure 3. The bottom panel presents a contour diagram of the observed oxygen-dominated ion conic distribution function in the central plasma sheet, measured by the HAPI instrument on Dynamics Explorer 1 on Nov. 14, 1981 at the geocentric altitude of  $2.0 R_E$  and invariant latitude of  $60^\circ$ . The top panel presents the theoretical contours for the same event based on the Monte Carlo simulation calculation. The contours are uniformly spaced with an increment of 0.4 in the logarithm of phase space density. The density of these ions at the observation point is approximately  $10 \text{ cm}^{-3}$ .

calculate the various moments of the conic distributions, for example, particle and energy fluxes (Crew and Chang, *Phys. Fluids*, **31**, 3425, 1988).

Armed with these theoretical tools, we found ourselves in a favorable position to attack the existing data set of ion conic events. In particular, with the right tools, it became possible to extract considerably more information concerning the physics of these ionosphere events and their relations to the global problems. For example, it is now possible to use observations of conic distributions to make indirect measurements

of the turbulence present during their formation. We have conducted such a combined theoretical/experimental investigation with investigators of the particle and wave experiments on the Dynamics Explorer 1 satellite (Crew *et al.*, J. Geophys. Res., **94**, 1989, in press).

(b) Ion Heating in the Polar Cusp/Cleft Region

We have also been collaborating with our visitor from Sweden, Dr. Mats André of the Viking Polar-Orbiting Satellite Science Team. Viking has often observed perpendicular heating of ionospheric ions both in the auroral region and in the polar cusp, and for most of these events, electric and magnetic wave data are available. Our study concentrated on some of the interesting events in the cusp where Viking observed locally heated ions (mostly in the polar cusp region). Here the plasma waves observed by the spacecraft should be sufficiently intense to be held responsible for the heating. We found that the plasma waves have a significant left-hand polarized component which should be efficient for cyclotron resonance heating of positively charged ionospheric ions. By using the observed wave amplitudes and polarization consistent with the observed data, we discovered that the electromagnetic ion cyclotron resonance mechanism can be employed to explain the observed ion data. Preliminary Monte Carlo calculations gave very encouraging results in the detailed description of these ion distributions. The method of calculation is similar to that employed for the central plasma sheet ions. However, since the wave intensity here is extremely intense and may occur over several thousand kilometers along the cusp field lines while the ions are heated in a rather narrow altitude range as they drift poleward due to the presence of a large convection magnetic field, the detailed calculational procedure is somewhat different.

As mentioned above, these Viking events were detected in the cleft/cusp region of the ionosphere/magnetosphere. *This makes our study even more interesting since the cleft region is known to be an important source of ionospheric ions entering the magnetosphere; yet no detailed discussion of the ion heating mechanism has been given previously by the geoplasma physicists for this region.* Similar events have been observed by the Dynamics Explorer 1 satellite, and we have obtained detailed, quantitative explanations for these events. In particular, it appears

possible, after a fashion, to follow the evolution of the heating distributions along the satellite trajectory. In addition, preliminary work (Peterson, *et al.*, in *Electromagnetic Coupling in the Polar Clefts and Caps*, Kluwer, 1989) suggests that the heating mechanism we have proposed is sufficient to account for the particle observations.

In addition to Dr. André, we have benefited by many useful interactions with and the collaborative research efforts of Drs. J. R. Jasperse and J. M. Retterer of the Air Force Geophysics Laboratory, Dr. J. D. Winningham of the Southwest Research Institute, Drs. W. K. Peterson, D. M. Klumppar and E. Shelley of the Lockheed Palo Alto Research Laboratory, Drs. R. Huff and D. Gurnett of the University of Iowa, Dr. N. Hershkowitz of the University of Wisconsin, Dr. H. Koskinen of the Finnish Meteorological Institute and Dr. R. Erlandson of the Applied Physics Laboratory, Johns Hopkins University, and Dr. M. Mellot of NASA Headquarters.

(c) Ion Heating and Electron Enhancement Near High Velocity Shear Regions and over the Polar Cap

Recently it has been reported (Basu *et al.*, *J. Geophys. Res.*, **93**, 115, 1988) that heated ion populations were detected by the DE-2 satellite in the auroral oval in regions where strong velocity shears were observed. Velocity shear can excite the Kelvin-Helmholtz instability and very low frequency MHD turbulence (Keskinen *et al.*, *J. Geophys. Res.*, **93**, 137, 1988). Such MHD turbulence can propagate up the field lines and become the low frequency electromagnetic ion cyclotron waves described above.

In addition, polar cap F-region sub-visual arcs, which are commonly observed during very quiet conditions when the interplanetary magnetic field is northward, have been found to represent boundaries (or shear) in the polar cap plasma circulation pattern. Along with these structures, enhanced broad-band low frequency waves have been detected. Coordinated optical, wave, particle and incoherent scatter radar measurements of such events are becoming available (Carlson *et al.*, *Geophys. Res. Lett.*, **11**, 895, 1984; R. Pfaff, private communication, 1988; Carlson *et al.*, data from the Polar Arc Campaign [to become

available in the near future)). We are collaborating with Drs. H. Carlson, J.R. Jasperse, E. Weber, and N. Maynard at the Air Force Geophysics Laboratory, Dr. J. M. Retterer of the Air Force Geophysics Laboratory, Dr. Su. Basu and Dr. J. D. Winningham of the Southwest Research Institute to investigate these events. We plan to study the ion acceleration phenomena for these events using the DE-2 data set, and the enhancement of electron concentration and their relevance to the polar thermospheric circulation, composition and structure using both the Polar Arc and DE-2 data sets.

## *2. Acceleration of Ionospheric Ions by Lower Hybrid Waves in the Discrete Auroral Region*

Near altitudes of  $1 R_E$  along discrete auroral field lines which terminate in the boundary layer region of the plasma sheet, strings of weak double layers have been detected along the geomagnetic field lines (Fig. 4). These double layers characteristically have potential drops on the order of 1 V over a spatial extent of several Debye lengths; recent observations confirm that they are generally propagating upward along the field lines. These double layers seem to set in intermittently in space and in time, and on the average are separated along the magnetic field lines at approximately 1 km intervals. They are probably produced by some sort of current driven nonlinear plasma instability (which will be discussed in Section III.B.1 of this report). It can be argued that during a magnetic substorm, upward field-aligned currents are the strongest at altitudes around  $1 R_E$  in the discrete auroral region. Such a region can have an altitudinal extent of over 1000 km. Thus, on the average, electron populations can be accelerated by the combined effect of these potential drops to energies beyond 1 keV. Indeed, keV electron beams have been detected streaming toward the ionosphere in the boundary plasma sheet. In addition to creating the visibly observable discrete aurorae in the E-region of the ionosphere, such electron beams can also excite a number of plasma instabilities in the supraauroral region. In particular, *in situ* observations have detected enhanced wave intensities near and above the lower hybrid resonance frequency.

In addition to the observed lower hybrid waves, simultaneous *in situ* measurements have also detected *counterstreaming electron*

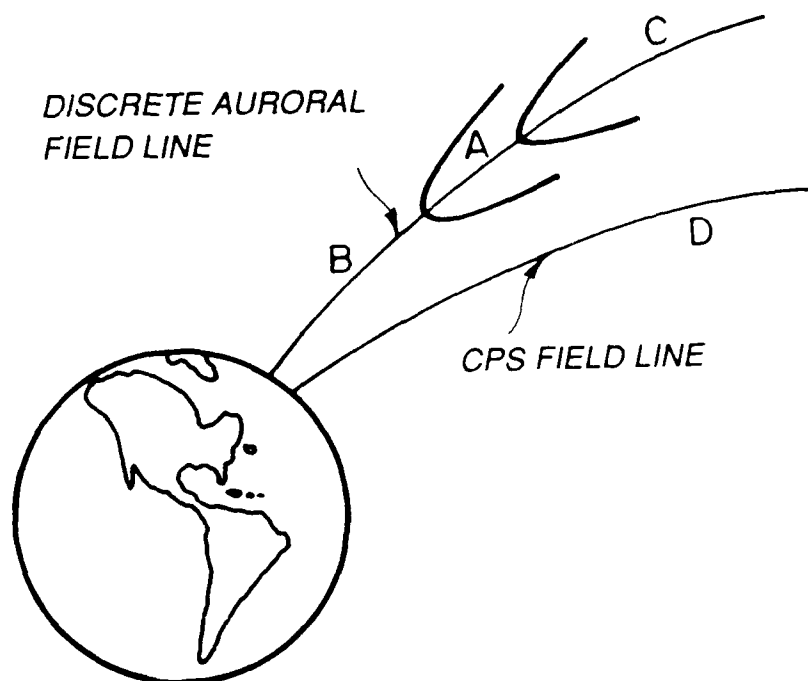


Figure 4. *Discrete Auroral Field Line*: (A) Region where weak double layers have been detected. (B) Region where lower hybrid waves, ion conics, and counterstreaming electrons have been detected. (C) Region where ion beams and electrostatic ion cyclotron waves have been detected. *Central plasma sheet (CPS) field line*: (D) Region where low frequency electromagnetic waves in the ion cyclotron range of frequencies and oxygen-dominated, shallow conics are detected. Note that regions A and C may overlap.

populations and ion conic distributions such as those described above. Above the kilovolt potential drops, on the other hand, upflowing keV ion beams have been detected along with enhanced emissions of electrostatic ion cyclotron modes.

In Section III.A.3, we will discuss our work on the generation of the lower hybrid turbulence in the high latitude ionosphere and local non-linear ion heating using two-dimensional particle-in-cell plasma simulation techniques. The evolution of the ion population, however, is a mesoscale problem: energy input to the ions is continuous over a range of altitudes along an auroral flux tube. Thus, analytic and Monte Carlo simulation techniques are much more appropriate. *Using diagnostics of the plasma simulation, one may obtain detailed information about the*



*wavenumber spectrum of the turbulence which is normally not observable, and from this construct a velocity-space diffusion operator to describe the wave-particle interactions. One may then introduce this heating term into the plasma kinetic equation in order to obtain an evolution equation for the conic distribution function.*

Typically the phase velocity of the lower hybrid waves is much greater than the thermal velocity of the ion distribution and this may be used to advantage to construct analytic solutions of this evolution equation. Specifically, this ratio is a small parameter that may be used to obtain asymptotically correct solutions to the heating portion of the equation. The effects of the magnetic mirror force and a possible field-aligned potential may then be added by means of an adiabatic transformation of the heated distribution (Crew and Chang, Phys. Fluids, **28**, 2382, 1985). (See Fig. 5).

These results may be compared and contrasted with the numerical treatment of the Monte Carlo simulation which simultaneously models both the heating and convective effects accurately. The comparison shows that the analytic solutions are in fact quantitatively useful far beyond their formal domain of validity, at least as far as the moments of the distribution are concerned. The major discrepancy is that the analytic treatment tends to make conics that are narrow in pitch angle. This is due to the neglect of what amounts to pitch angle scattering of the distribution as it evolves up the flux tube under the effects of the mirror force. The energy distribution of the conic is rather well approximated, however.

This work has been performed in collaboration with Drs. John M. Retterer and John R. Jasperse of the Air Force Geophysics Laboratory.

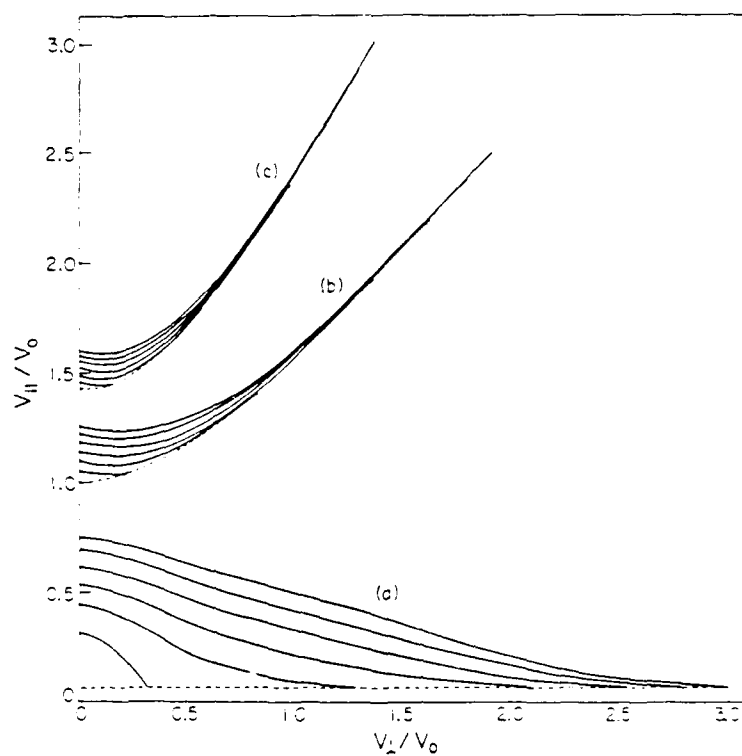


Figure 5. Evolution of an hydrogen ion conic based on the analytical solution using the two-stage approximation. Typical ionospheric conditions are assumed, and the root mean square electric field intensity  $E_w = 33$  mV/m. Cases (a), (b), and (c) are at altitudes 10, 2500, and 5000 km above the base of the diffusion layer, which is 10 km thick.

### 3. Two-dimensional Particle-in-cell Plasma Simulation of High-Latitude Lower Hybrid Turbulence and Charged Particle Acceleration

Although the one-dimensional simulations discussed in the preceding section have demonstrated that this mechanism can be effective for particle acceleration, a number of interesting phenomena can be realized only in higher dimensions. For example, the convective linear growth rates and dispersion of VLF waves on the whistler resonance cone depend crucially on the angle of propagation with respect to the magnetic field, but one-dimensional simulations can study only a single propagation angle at a time. Additionally, mode-coupling processes cannot be studied in complete generality in one-dimension either, because

wave vectors are constrained to be aligned in the same direction.

We have performed two-dimensional plasma simulations of this phenomena of lower hybrid-turbulence generation and ion acceleration. These results are described in a recent paper of ours (Retterer and Chang, *Physics of Space Plasmas*, **8**, 309, 1989). Some of the more important findings are highlighted below.

Fig. 6 summarizes the energetics of two typical simulation runs. Plotted as a function of time in this figure are the energy densities of the several species in the plasma and the electrostatic energy of the waves; all energy densities are normalized to the initial energy density of the electron beam population. Following the linear growth and saturation of the waves, we note in the figure the gain of energy by the ambient electron population and the light ion population.

Because of the restricted perpendicular mobility of the electrons, their acceleration occurs primarily parallel to the magnetic field. The ions on the other hand are predominantly heated in the perpendicular direction. These effects are illustrated for two typical simulation runs in Figs. 7 and 8.

Much of the interesting physics of the simulation is contained in the evolution of waves presented in Fig. 9. In the earlier snapshot, we see from the vertical alignment of the contours and spacing that only the linearly excited waves are present. These waves propagate in the direction of the beam velocity. In the later snapshot, we see that the linearly excited waves have degenerated into turbulence containing fluctuations on many spatial scales and in many directions. This process aids particle acceleration by making excited waves which are more accessible (via their reduced phase velocity) to the low energy ions and electrons. We found that the cascading of energy among these waves in the lower hybrid range of frequencies is governed by a coupled set of nonlinear Zakharov or Schroedinger equations. The complete turbulent wave-particle interaction picture is then obtained by adding dissipation to the equations.

We have compared our analytical results to experimental observations. In particular the recent MARIE rocket campaign over Greenland has provided us with what is probably the most complete and detailed

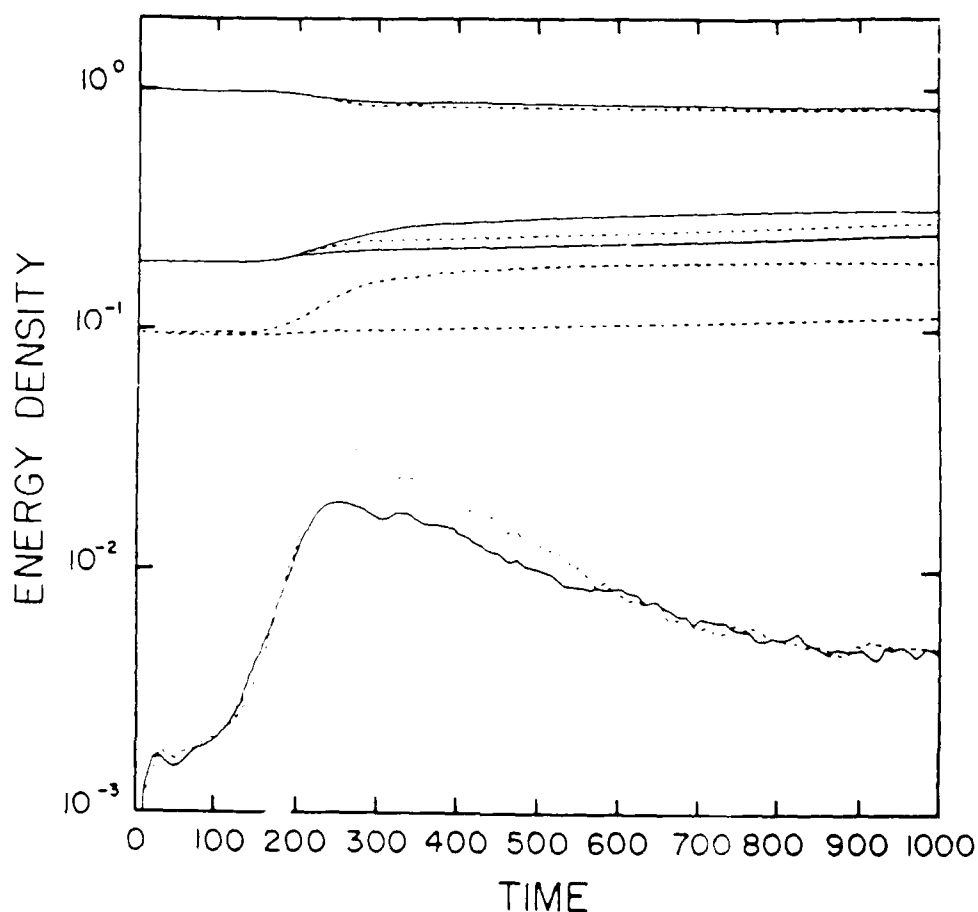


Figure 6. Energetics of two runs of model simulations. The solid curves (s) give the evolution of the energy densities of the species in a run with only light ions, while the dashed curves (d) give the energy densities in a run with both light and heavy ion species. From the top at the right-hand side, the species are: beam electrons (s,d) light ions (s), ambient electrons (d,s), light ions (d), heavy ions (d), and the electrostatic energy (d,s).

set of ionospheric observations of the low-altitude transversely accelerated ions. Our simulations provide a model for the processes occurring during the formation of ion conics near auroral arcs, as reported in these observations. From the *in situ* plasma and wave measurements, a strong correlation is found between VLF wave intensity and energetic ion flux; there is preferential acceleration of hydrogen over

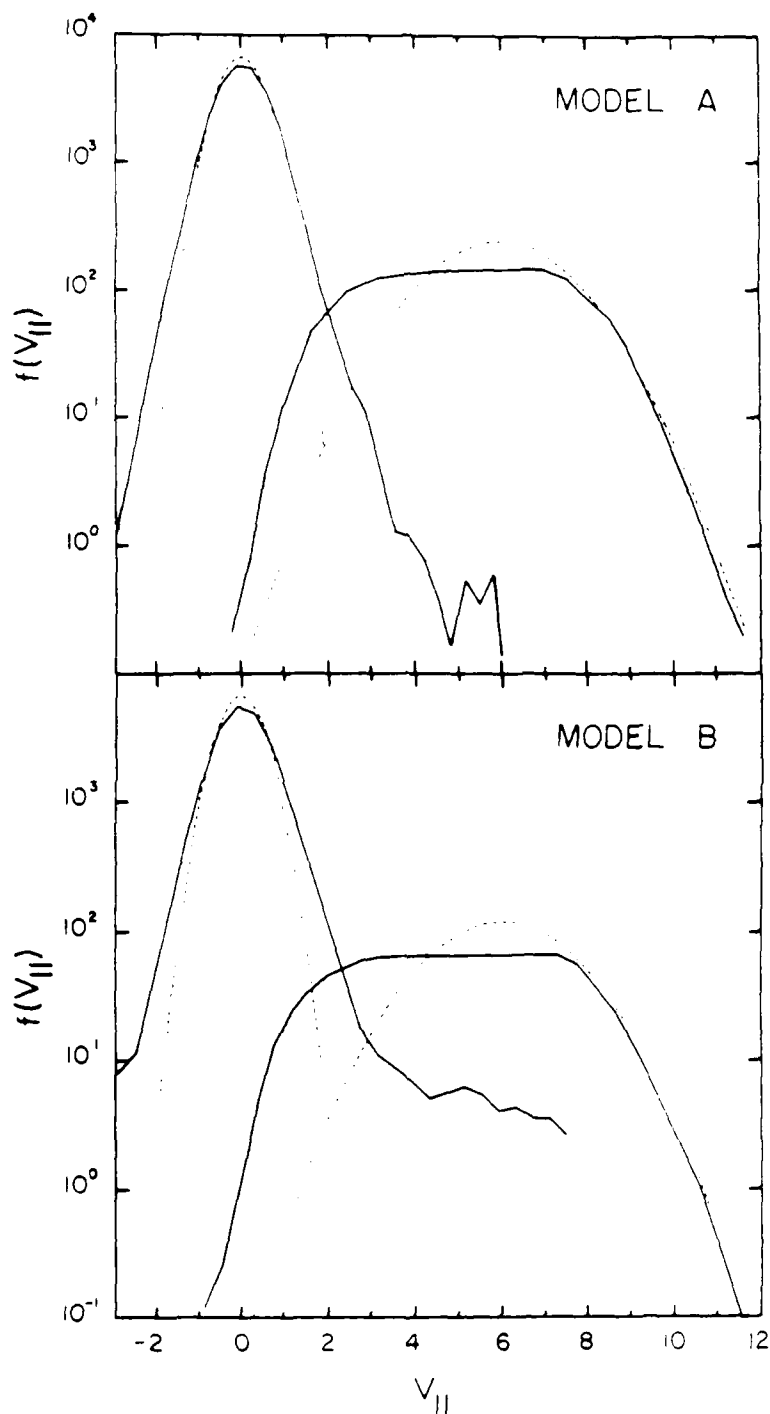


Figure 7. Electron parallel-velocity distributions for two 2-D simulation runs. The dashed curves are the initial distributions, and the solid curves are following wave saturation.

oxygen; and enhancements of field-aligned electron fluxes are found. The frequency spectrum of the VLF turbulence around the lower hybrid frequency shows structures spaced at the hydrogen gyrofrequency, suggesting that ion cyclotron damping of the waves is responsible for the acceleration. The amplitude of the VLF turbulence is several tens of mV/m; this is strong enough to account for the ion energies. Finally, the form of the ion velocity distribution has the high energy tails that

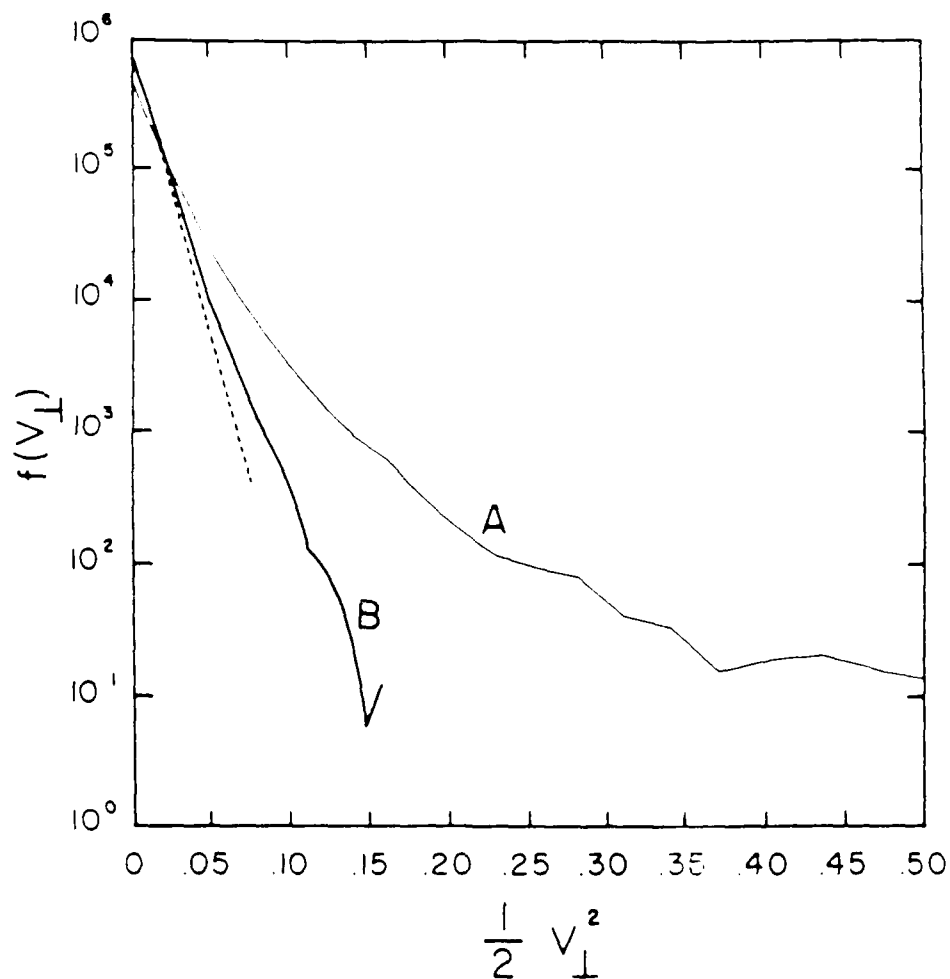


Figure 8. Ion perpendicular-velocity distributions following the time of wave saturation in two 2-D simulations. The dashed line is the initial Maxwellian distribution for both cases.

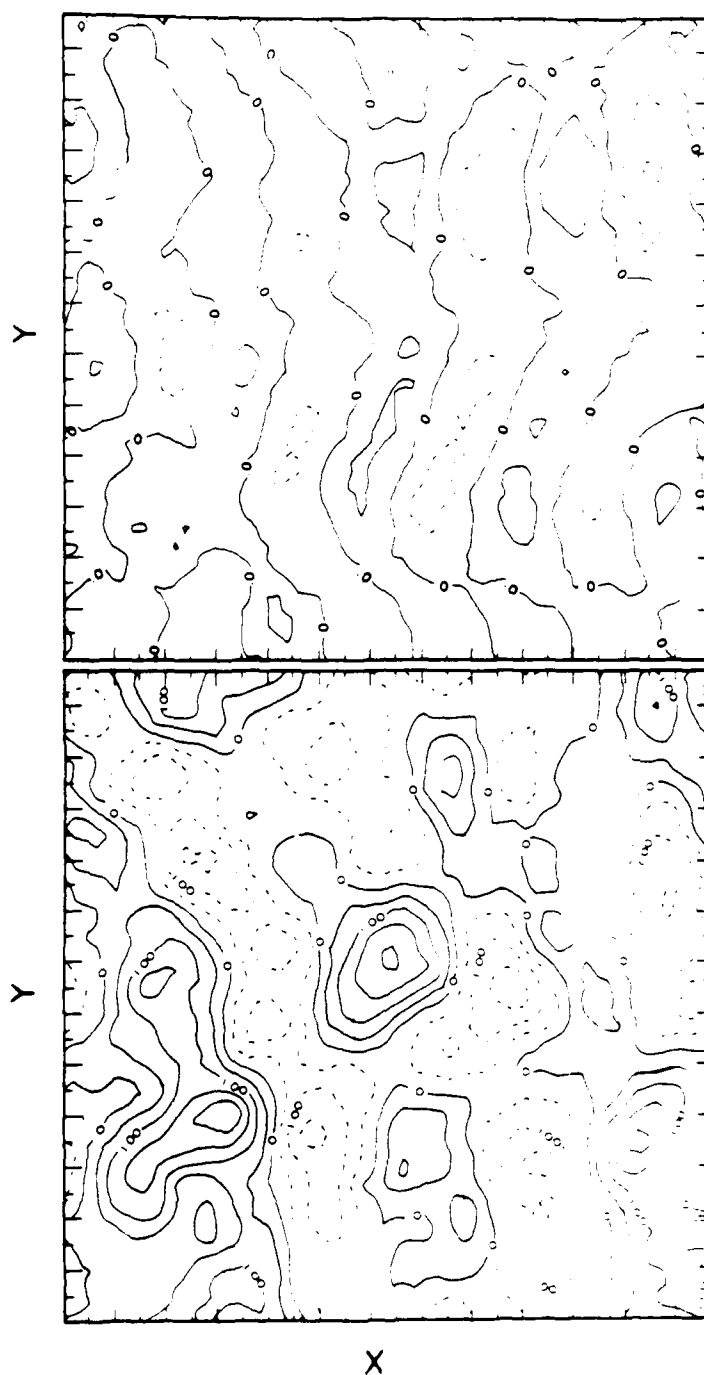


Figure 9. Snapshots of the electric potential prior to wave saturation (top) and following saturation (bottom) in a two-dimensional simulation run.

are characteristic of the acceleration observed in the simulation. In addition, there are provocative new observations of intense VLF wave packets (spikelets) observed in conjunction with the transversely accelerated ions.

These exciting results involving high-latitude strong ionospheric turbulence and particle acceleration are conducted with the enthusiastic interactions of our colleagues: Dr. Andrew Yau from the National Research Council in Canada, Professor Paul Kintner of Cornell University, Drs. J. M. Retterer and J. R. Jasperse of the Air Force Geophysics Laboratory. We have reported some of these research findings at the Third International School for Space Simulation at Beaulieu, France in June 1987, the 1987 Fall Meeting of the American Geophysical Union in San Francisco, CA, the International Conference on Auroral Physics, held at Cambridge, UK in July 1988, and the 1988 Cambridge Workshop in Theoretical Geoplasma Physics held at MIT in June, 1988.

### **III.B. Studies of Inhomogeneous Plasma Turbulence in the Auroral Region**

A major simplification common to studies of plasma turbulence beyond the linear regime is the assumption that the plasma medium is uniform. However, it has long been recognized in linear studies of wave propagation in the ionosphere and magnetosphere that spatial inhomogeneities play an important role in determining the characteristics of the observed waves. It has also been recognized that the presence of inhomogeneity can modify existing plasma instabilities and create additional ones.

We have launched an extensive program to study the generation and evolution of plasma turbulence in inhomogeneous media, using asymptotic techniques, WKB approximations and particle plasma simulation.



### *1. Lower Hybrid Wave Turbulence*

Here our focus is on waves which lie on the whistler resonance cone, having frequencies between the local ion and electron plasma frequencies. After these waves are excited at high altitudes through wave-particle resonance with precipitating auroral electrons, they propagate into plasmas of higher density as they propagate toward the earth. Consequently the frequency of the lower hybrid resonance rises to meet the wave frequency: approaching this resonance, the wave is not allowed to continue its propagation on the whistler dispersion surface; mode coupling and conversion processes come into play and dissipation through wave-particle interaction with the ambient plasma becomes significant.

In the linear regime, the phenomenon of mode conversion can be described theoretically by matching the WKB solutions for the propagation region to an asymptotic analysis about the resonance layer to obtain connection coefficients that give the proportion of the wave amplitude reflected from the layer, transmitted through it, converted into other modes, and absorbed by the plasma within it. In the nonlinear regime, of course, wave-particle interactions must also be considered.

Some of this work is reported by Crew (J. Plasma Phys., **41**, 119, 1989) and Retterer and Chang, (Physics of Space Plasmas, **8**, 309, 1989).

### *2. Low Frequency Turbulence*

As discussed above in Section III.A.1 we have constructed a satisfying explanation of ion heating and conic formation along magnetic field lines which connect into the central plasma sheet. Although this theory has been able to explain the evolution of ion populations given an observed turbulent electric field spectrum, it fails to explain the origin of the broadband turbulence. The apparent absence of local sources suggests that a more global approach must be considered. We decided to consider whether a turbulent spectrum generated in some region of the magnetosphere might then propagate into the region where it can resonate with the ions.

We have identified a plausible source region for the turbulence associated with the central plasma sheet conics (Johnson *et al.*, Geophys. Res. Lett., **16**, 1989). We have shown that equatorially generated low frequency waves could propagate to low altitudes and acquire a sufficient fraction of left hand circularly polarized component and heat the heavy ions ( $O^+$ ).

In the equatorial region near geosynchronous orbit on the night side, anisotropic ion distributions are often observed. As ions are injected earthward from the magnetotail, they drift adiabatically about the earth along drift shells. Because the shell on which a particle is constrained to move depends on the equatorial pitch angle, initially isotropic distribution functions tend to develop thermal anisotropies and acquire anomalous loss cones. These ion distributions can excite waves both above and below the hydrogen gyrofrequency in the equatorial region. We have shown that both types of waves can propagate along the geomagnetic field lines and propagate to the auroral region. Since the equatorial proton frequency is in consonance with the oxygen cyclotron frequency in the auroral region where ion heating takes place, these waves can be the auroral turbulence that are responsible for the heating of oxygen ions.

Although it is well documented that waves below the equatorial proton frequency can be generated by the anisotropic proton distributions and that they can propagate to the auroral region as PCI waves, waves with frequencies higher than the equatorial proton frequency have not received much attention. We have considered the generation, propagation, and mode conversion of these waves. In particular, we have included a thermal spread in the hot ion distribution function which we have modeled with subtracted Maxwellians using the parameters listed in Table I below. We found that in addition to the nearly perpendicularly propagating electrostatic modes, there exists a broadband of unstable obliquely propagating electromagnetic magnetosonic waves which can propagate out of the equatorial region.

Table I. Plasma Model ( $B = 0.001$  G)

Species	$n(\text{cm}^{-3})$	$T_{\parallel}(\text{keV})$	$T_{\perp}(\text{keV})$
cold $e^{-}$	66.6	0.001	0.001
cold $H^{+}$	65.0	0.001	0.001
hot $H^{+}$	2.3	10.0	10.0
	0.7	10.0	3.0

As the waves (originally right hand circularly polarized) propagate toward the auroral zone, the magnetic field gradient converts a portion of it into a left hand circularly polarized component which, in turn, can heat the oxygen ions. In Table II, we present some of the calculated numerical

Table II. Transmission and Coupling Coefficients

$n_O/n_H$	$\tan^{-1}(k_{\perp}/k_{\parallel})$	$C$	$T$	$R$
0.05	$18^{\circ}$	10%	0%	100%
0.01	$27^{\circ}$	10%	18%	67%

results. We have considered an  $O^{+}-H^{+}$  plasma in the auroral region at  $2 R_E$  along a field line with invariant latitude  $60^{\circ}$ ,  $n = 100 \text{ cm}^{-3}$ ,  $B=0.05$  G, and  $L_B = 1 R_E$ . We found that for sufficiently low concentration of oxygen ions, a few percent of left hand polarized component is obtained at the heavy ion gyrofrequency via mode conversion and tunneling. These results are consistent with the ion heating theory of Chang *et al.* (Geophys. Res. Lett., **13**, 636, 1986) which required only a small fraction of the waves to be left hand circularly polarized.

### III.C. A Kinetic Treatment of the Nonclassical Polar Wind

Theoretical modeling of the polar wind has generally taken on one of two forms: At higher altitudes, where collisions are usually neglected, a kinetic treatment for the evolution of the phase-space density requires only the mapping of the distribution along particle trajectories. At lower altitudes, where collisions are important, kinetic treatments have been considered too complex, and all the descriptions are based on moment equations. However, collision rates in plasmas are generally highly dependent on velocity, this tends to create velocity distributions that cannot, in general, be easily characterized by the few moments in a moment theory.

On the other hand, particle measurements (ISIS and DE1) have revealed field-aligned, "cigar-shaped" pitch angle distributions in the photoelectron spectrum. The observed distributions consist mainly of outflowing terrestrial photoelectrons, but sometimes include an inflowing component with a variable high-energy cutoff that has been attributed to reflection by a varying potential drop above the satellite. In general, these distributions carry little current but appreciable heat flux.

Such observed distributions are not predicted by polar wind calculations based on moment theories; the heat flow models used in moment calculations can force the electron temperature anisotropy to develop in the opposite sense:  $T_{\perp} > T_{\parallel}$ . Clearly, a kinetic treatment of the polar wind to describe the transition from the collisional to the collisionless regime is essential for the understanding of this phenomenon.

We have completed a Monte Carlo calculation of the evolution of a model photoelectron distribution above the polar cap based on a fully global evolutionary collisional kinetic model. Fig. 10 gives the calculated contour plots of the photoelectron distribution  $f$  at altitudes of 600 (bottom) and 22,400 (top) km. The numbers label  $\log_{10}$  contours of  $f$  in  $\text{sec}^3/\text{km}^6$ . Two effects are clearly noted: (1) the formation of a thermal component at low altitude, and (2) the formation of an energetic field-aligned component at higher altitudes.

In Fig. 11, we have plotted the calculated (full line) and observed (dashed line) distribution functions (for a particular conjugate event measured by the HAPI and LAPI instruments aboard the DE1 and 2

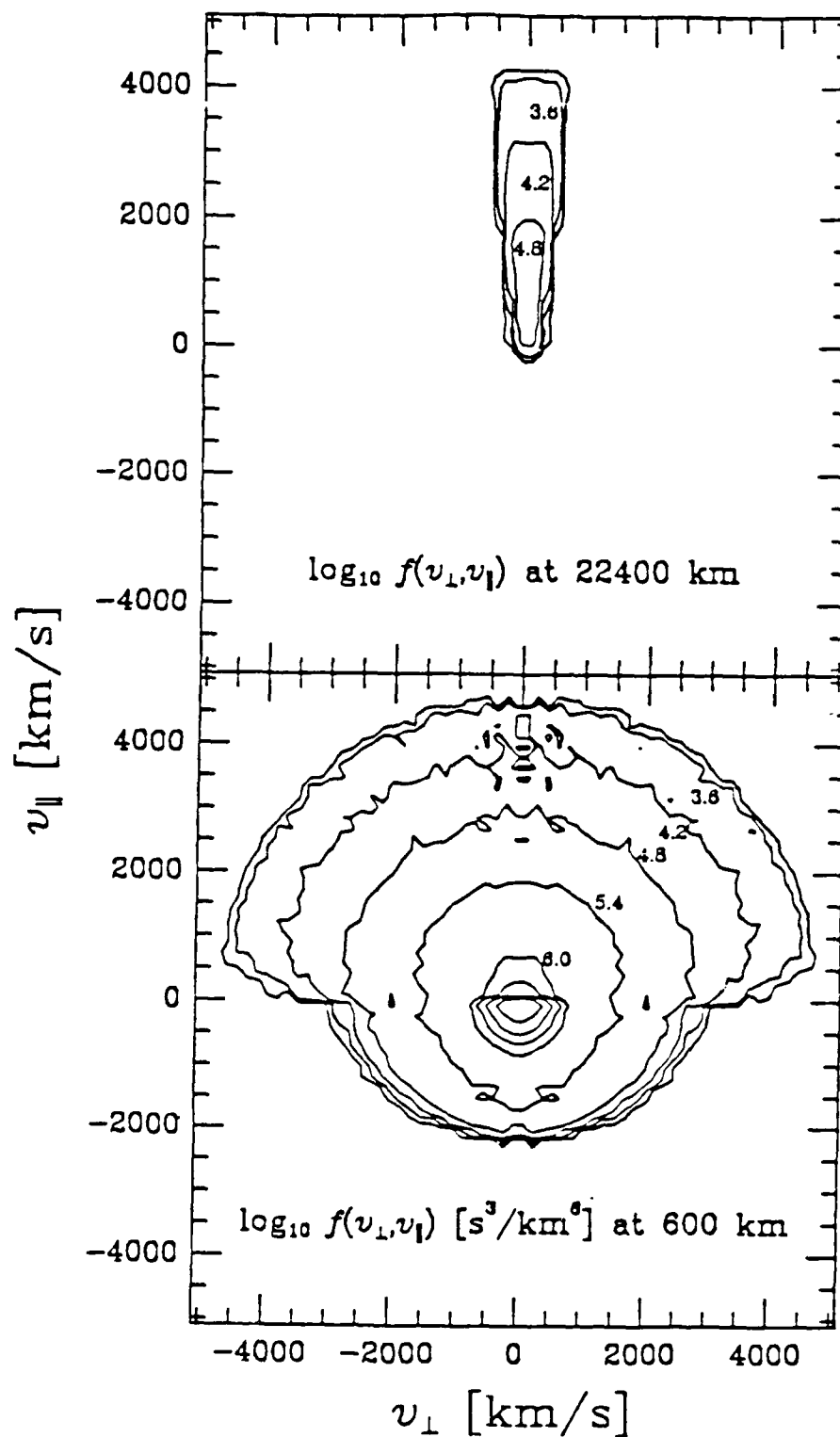


Figure 10. Contour plots of the photoelectron distribution at altitudes of 600 (bottom) and 22,400 (top) km from the Monte Carlo calculation.

satellites) at the same pitch angle, at 600 (bottom) and 22,400 (top) km. For the low altitude plot, this pitch angle was chosen to coincide with that of an energy analyzer on the spin stabilized LAPI instruments,  $15^\circ$  and  $165^\circ$ . At higher altitudes, the HAPI instrument on the DE1 satellite is spinning, so we may chose an angle near  $180^\circ$ , which corresponds to field-aligned upstreaming particles. In this way, we avoid uncertainties due to the coarse pitch angle evolution of the LAPI instrument in the upflowing direction. The correspondence between theory and data is quite remarkable.

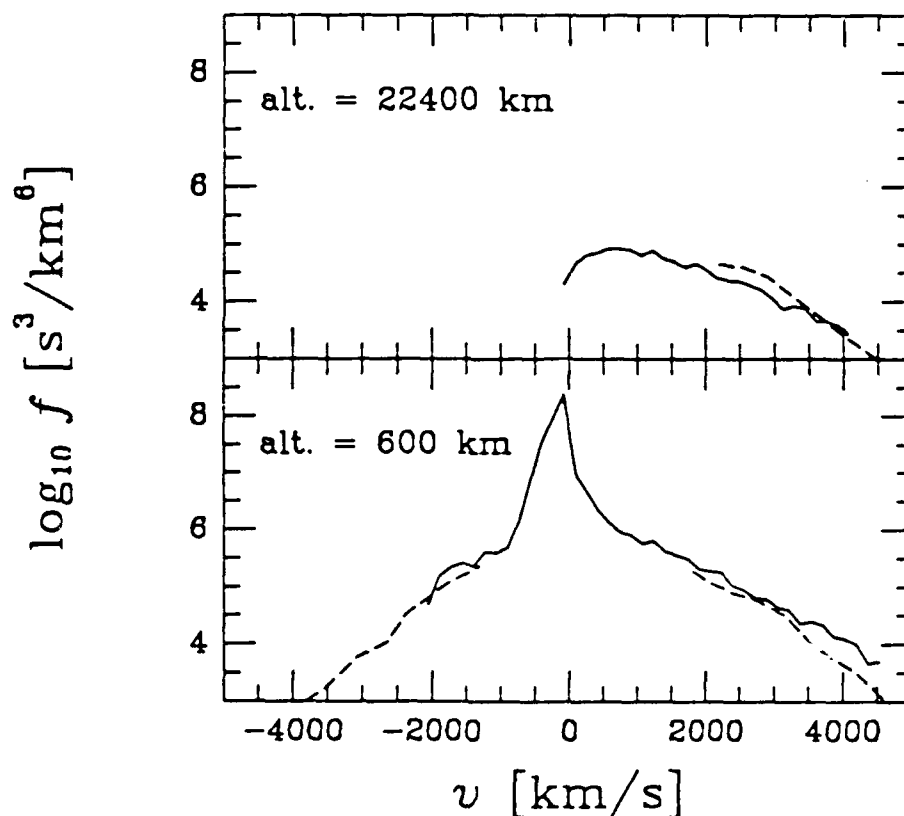


Figure 11. Comparison of calculated (full line) and observed (dashed line) distribution functions at the same pitch angle, at 600 (bottom) and 22,400 (top) km.

This work just appeared as an article in the Geophysical Research Letters (Yasseen *et al.*, **16**, 1023, 1989). Our calculations indicate that the photoelectrons contribute a significant nonclassical heat flux and must be accounted for in accurate polar wind studies.

We are collaborating with Dr. John M. Retterer of the Air Force Geophysics Laboratory of Boston College and Dr. J. D. Winningham of the Southwest Research Institute in these studies.

#### III.D. Double Layer Formation and Ion Hole Theory along Auroral Field Lines

Double layers have been suggested as a field-aligned, particle acceleration mechanism for auroral plasma. Supporting evidence comes from S3-3 and Viking satellite data which have shown that double layers exist on magnetic field lines in the auroral acceleration region (Temerin *et al.*, Phys. Rev. Lett., **48**, 1175, 1982; Koskinen *et al.*, Physics of Space Plasmas (1987), Scientific Publishers, Inc., Cambridge, MA). The standard explanation for their existence is the development of nonlinear plasma fluctuations from the *linear* ion acoustic instability. However, the low electron to ion temperature ratio  $T_e/T_i$  and electron drift speed  $v_D$  in the auroral acceleration region perversely implies the stability of ion acoustic waves.

Recently, we proposed an alternative explanation in terms of the *nonlinear* formation and growth of ion holes. Ion holes are localized depletions in the ion phase space density that form when the phase space density is turbulently mixed. Because the plasma is charge-neutral, an individual hole has a negative potential. This potential nonlinearly traps the surrounding ions, thereby forming a localized nonlinear plasma equilibrium, or a so-called BGK mode. Let  $f_{0e}'(v)$  denote the velocity gradient of the mean electron distribution function. Hole growth occurs for  $f_{0e}'(v) \geq 0$  since a charge imbalance forms across the hole as a net number of electrons are reflected by the hole's potential. This charge imbalance gives the hole its double layer potential structure. The holes develop intermittently in phase space and, in contrast to linear ion acoustic waves, can grow in a drifting plasma with arbitrary  $T_e/T_i$  and any finite  $v_D$ .

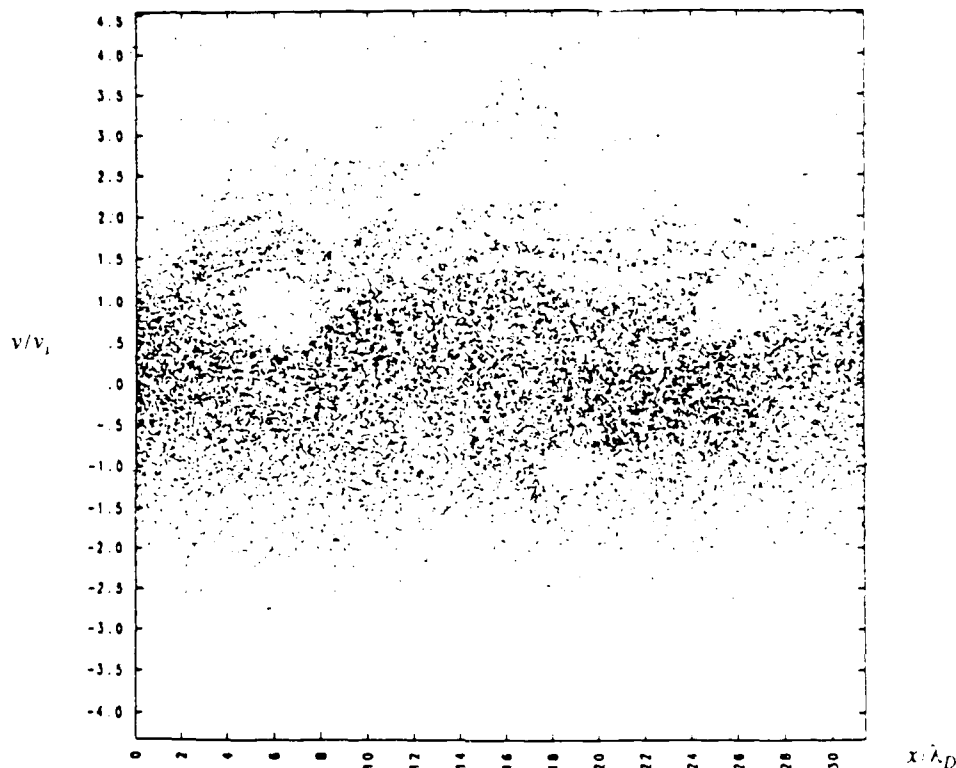


Figure 12. Growth of ion phase space holes in a linearly stable simulation plasma. (More than a million particles were used in the simulation.)

We have compared the predictions of our hole model with the existing satellite data (Tetreault, *Geophys. Res. Lett.*, **15**, 164, 1988). Our model allows for detailed calculations of instability thresholds, as well as characteristic double layer amplitudes, potential drops, speeds and scale sizes. The results of the detailed comparisons are exceptionally favorable.

This explanation of double layer formation was obtained taking the point of view of a one-dimensional Vlasov plasma. We propose to enlarge the model's applicability by including the anisotropic three-dimensional effects due to the presence of an ambient magnetic field. Three dimensionality is important since the satellite data has shown double layers in the presence of electrostatic ion cyclotron (EIC) waves. Our immediate plan is to include EIC waves in our nonlinear hole instability analysis.



Nevertheless, the excellent agreement between the satellite data and the one-dimensional model suggests that, as far as nonlinear trapping phenomena parallel to the magnetic field is concerned, the one dimensional hole model should suffice. Further support comes from two-dimensional computer simulations (Barnes *et al.*, Phys. Fluids, **28**, 155, 1985) which indicated that the presence of EIC waves had no noticeable effect on the parallel dynamics of the structure of the double layer.

Our investigation on the effect of EIC waves (Tetreault, Physics of Space Plasmas (1989), Scientific Publishers, Inc., Cambridge, MA, in press) also supports the 2D simulation results. Thus, if we invoke the disparities between the hole growth rate and the ion gyrofrequency, and between parallel and perpendicular scale lengths, then the fluctuation dynamics breaks up into two parts: the parallel hole/double layer model described above and a perpendicular EIC model. Essentially, the effect of the plasma dynamics on the Poisson's equation is to predict a potential structure induced by the parallel dynamics and a dielectric constant describing the EIC waves.

We have benefited from discussions with Dr. H. Koskinen of the Finnish Meteorological Institute and Professor Paul Kintner of Cornell University with regard to the exciting new data recently obtained by the Viking satellite.

### **III.E. Flux Transfer Events and Ionosphere-Magnetosphere Coupling**

Satellite observations (ISEE, UKS, DE, *etc.*) have also confirmed that nonlinear structures (magnetic bubbles) are an essential component in anomalous reconnection processes in the Earth's ionosphere and magnetosphere. Russell and Elphic (Space Sci. Rev., **22**, 681, 1978) discovered such a nonlinear phenomenon in the dayside magnetopause region via the ISEE satellites and called it the flux transfer event (FTE). They suggested that an FTE represents a time dependent form of patchy reconnection carving a hole through the magnetopause allowing a terrestrial magnetic flux tube connection with a magnetosheath tube. In fact, it has been suggested that such an event might have been detected by the DE satellites in the high latitude, low altitude ionosphere (Smith,

*et al.*, Physics of Space Plasmas (1988), Scientific Publishers, Inc, Cambridge, MA, 1989), indicating that FTEs can be quite important in ionosphere-magnetosphere coupling processes. The FTE generally has a diameter of  $1 R_E$  and contains a twisted magnetic field line. In 1985, Lee and Fu (Geophys. Res. Lett., **12**, 105, 1985) argued that this type of flux transfer event could be represented by multiple X-point reconnections. More recently Scholer (Geophys. Res. Lett., **15**, 291, 1988) suggested that the FTE event in the dayside magnetopause could be represented by a model of X-line bursty reconnection.

Models of these phenomena have focused on linear instabilities—in this case, the tearing mode instability. However, as with the reconnection in laboratory plasmas, (*e.g.*, disruptive instability in tokamak fusion devices), the collisional resistivities behind the linear tearing instability are too small to explain the fast reconnection (relaxation) rates observed. Historically, models of such laboratory reconnection have focused on coherent, laminar reconnection processes of plasma flowing in and out of isolated X-points punctuating separate reconnection islands. At present, terrestrial and solar reconnection models are also of this type. For the laboratory case, such models failed to explain the observations. It was subsequently determined by detailed laboratory measurements and computer simulations that the turbulent relaxation (reconnection) proceeded from the nonlinear interaction of many overlapping island structures and the subsequent stochastization of the magnetic field lines.

An understanding of these nonlinear phenomena requires a nonlinear model. Such a nonlinear model exists—the MHD clump instability. (See, *e.g.*, Tetreault, Phys. Fluids, **31**, 2112, 1988; Phys. Fluids, **32**, 511, 1989). The MHD clump instability is the MHD plasma analogue of the Vlasov clump/hole instability which has successfully explained for us the double layer problem as discussed in Section III.D above. Briefly, the instability can be understood as follows. As multiple X-point resonances approach, their associated islands overlap and the magnetic field lines become stochastic. However, neighboring field lines feel approximately the same forces and thus tend to diffuse together. MHD clump fluctuations are current carrying bundles of such correlated magnetic field lines. As the stochasticity ensues, the mean current density is

diffused (turbulently mixed) by a self-consistently generated "anomalous" resistivity. (This nonlinear resistivity differs from standard laminar MHD reconnection used in calculations or simulations, where the resistivity is either chosen arbitrarily based on some *ad hoc* hand-waving arguments or produced artificially by some sort of numerical diffusion process.) The clump fluctuations grow in a fashion similar to the tearing mode, but nonlinearly and with a much larger growth rate. The turbulent mixing of the current density reduces (minimizes) the mean energy subject to magnetic helicity conservation, so the plasma relaxes to the force-free Taylor state. This MHD clump model has been quite successful in explaining the turbulent relaxation observed in laboratory reversed field pinch plasmas.

Though present observations are too sparse to confirm it, we suspect that similar multiple X-points and field line stochastization are also a highly probable occurrence in terrestrial ionosphere and magnetosphere. This would seem particularly true of the magnetosphere/solar wind boundary where strongly varying magnetic shear in both space and time are likely. The intermittent appearance of multiple, closely packed resonances would seem unavoidable. We believe that the MHD clump model will provide a novel approach to the understanding of terrestrial reconnection phenomena and will be a new focus on the study of flux transfer events. Our ultimate goal in this area of research is the estimation and prediction of relevant ionospheric signatures due to the transport, diffusion, and excitation of the fluctuations of magnetic field and other plasma properties traceable to the magnetopause-low latitude boundary layer through magnetic reconnection and FTEs.

### III.F. Auroral Kilometric Radiation and Relativistic Magnetized Anisotropic Plasmas

Intense electromagnetic kilometric radiation has been detected from the auroral region during magnetic substorms. The emission is close to the local electron cyclotron frequency and predominantly X-mode. The total power emitted has been estimated to reach  $10^9$  W during intense substorms. It has been suggested by Wu and Lee (Ap. J., **230**, 621, 1979) that the emission mechanism of this "auroral kilometric radiation" (AKR) is due to a relativistic plasma maser effect primarily associated with the trapped electrons which originate in the plasma sheet during a substorm. Such a type of electron-cyclotron maser instability has been studied for the case of an anisotropic electron velocity distribution (*e.g.*, Pritchett, Phys. Fluids, **29**, 2919, 1986 and references contained therein) and compared favorably with the observed wave data (Shawhan and Gurnett, Geophys. Res. Lett., **9**, 913, 1982).

We have developed a theory of fully relativistic plasma waves and instabilities in an external magnetic field, based on the relativistic Vlasov-Maxwell equations, for a wide variety of physical systems (Yoon and Chang, J. Plasma Phys., 1989, in press). Our analysis is, of course, fully general and has applications also to other planetary radio emissions as well as astrophysical sources such as the extragalactic radio jets (Yoon and Chang, Ap. J., 1989, in press). In particular, we have derived an exact expression for the dielectric tensor for a system of relativistic magnetized plasmas, whose microscopic momentum distribution function incorporates an energy anisotropy, momentum-space inversion, and a net drift along the magnetic field. Previously, a similar analysis has been carried out for the relativistic thermal equilibrium distribution by Trubnikov (Plasma Physics and the Problem of a Controlled Thermonuclear Reaction, p. 104, 1958). Our expression for the dielectric tensor generalizes Trubnikov's result to the case of nonideal, nonthermal plasma distributions.

We have considered various limiting situations, including the weakly relativistic case (applicable to the analytical study of auroral kilometric radiation) and the electromagnetic Weibel instability due to temperature anisotropy. (Yoon, 1989).

### III.G. Plasma Radiations in the Low-Altitude Ionosphere due to Moving Conducting Objects

There are many situations of practical interest in the Earth's ionosphere which involve the motion of a conducting body immersed in a magnetized plasma medium. Examples include the long antenna booms on scientific satellites, the long conducting tether of a tethered satellite and the space station. In all cases, there will be a nonnegligible, motionally-induced potential across the structures. The resulting induced current flow through the body and the ionosphere generates plasma radiations of Alfvén and lower hybrid waves. This phenomenon of plasma wave radiation due to the motion of a spacecraft in a magnetized ionosphere is of extreme importance: it represents an important inefficiency and an undesirable source of noise in the system.

Since the current source is moving, when viewed from a fixed frame, the current will appear to be AC. The problem of radiation from induced AC currents into the surrounding plasma is of interest for two reasons. Firstly, for large space structures such as the long antenna booms on a scientific satellite or the space station, there may be inductive coupling between the power distribution system and the motionally induced current flowing through the structure. Secondly, for large structures such as the electrodynamic tether, one potential use is as a broadcasting antenna to communicate information to the surface of the Earth. The major difference between these two cases is that in the former the system is passive, that is the current flow in the structure is due only to the induced potential while in the latter the system is active, *i.e.*, current is actively driven through the tether. For passive systems, it is desirable that the radiated power be as small as possible since it represents a loss of power from the structure. Also, for the wave-measuring antennae, the radiations may inject spurious signals into the desired measurements. For an active system like a broadcasting antenna, the radiated power should be as large as possible so as to achieve a high signal to noise ratio.

We have developed a general formalism which permits us to compute the response of the ionospheric plasma to an external current source. We derived an integral equation which relates the source

current to the electrical properties of the conducting body. This formalism enables us to estimate the total radiated power for moving conductors. We find that in general the radiation is produced at all frequencies for which one of the plasma modes has zero phase velocity in some direction. The mechanism by which this radiation is produced is analogous to Cherenkov radiation. In the cold plasma approximation, there is generally radiation into three frequency bands. Important scaling laws are derived for plasma radiations in the MHD and lower hybrid frequency ranges.

Some preliminary results in this study were recently published in a Journal of Geophysics Research article (Hastings *et al.*, **93**, 1945, 1988).

### **III.H. Detailed Comparison with Experiments**

One major focus of our current research is to compare in detail our developed model calculations with actual experimental observations. We have addressed three areas where sufficient detail for meaningful comparisons with the theory are in principle possible.

#### *1. Gyroresonance Generated Ion Conic Populations*

As described in Section III.A.1, we have enjoyed considerable success in explaining the occurrence of the central plasma sheet oxygen-dominated ion conics in terms of an electromagnetic ion cyclotron resonance theory (Chang *et al.*, Geophys. Res. Lett. **13**, 636, 1986; Retterer *et al.*, Phys. Rev. Lett., **59**, 151, 1987; Crew and Chang, Phys. Fluids, **31**, 3425, 1988). However, that was not a unique event but rather was typical of a class of conic events which may be identified within the Dynamics Explorer data set. It is therefore important to apply the theory to some of these other events both to put the theory to the test as well as to establish a "class" of understood phenomena.

Important candidate events for such an analysis are the conics reported by Klumpar, Peterson and Shelley in 1984 (J. Geophys. Res., **89**, 1779). In addition to being suitable for such a rigorous application to the theory, there is also an important issue to be resolved. Namely, in the absence of other plausible explanations, these authors suggested that these events were explainable via a two-stage acceleration

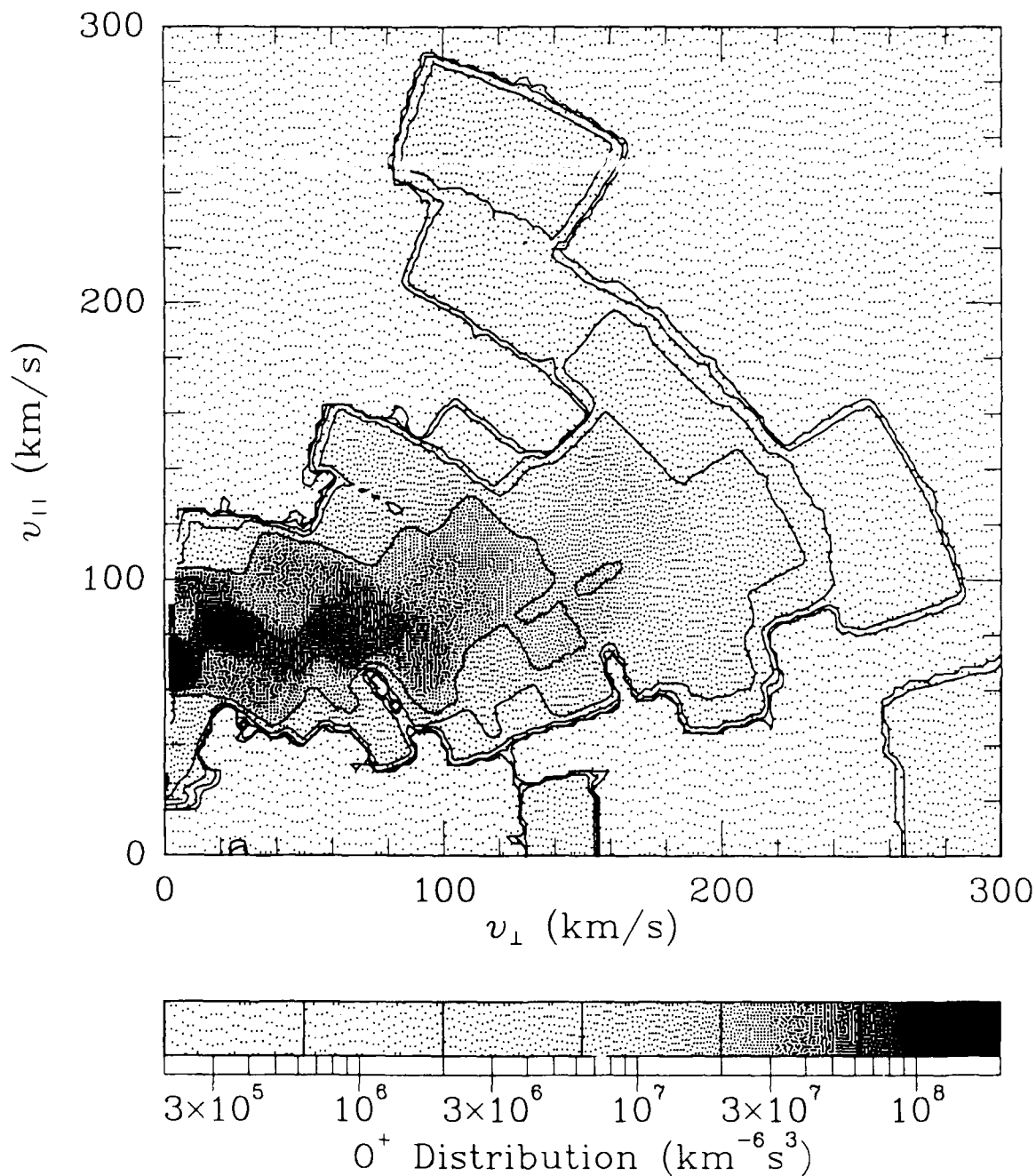


Figure 13. Conic distribution  $f_o(v_{\perp}, v_{\parallel})$  constructed from four spins of EICS data near UT 74800 s on day 81288. Contours are placed at half decades, and the darker regions denote the greatest phase space density.

mechanism: transverse acceleration, possibly achieved by wave-particle interaction followed by subsequent acceleration through a parallel electric potential drop. A plausible case has been made for an explanation solely via wave-particle interactions, the geoplasma community will benefit by not being obliged to look for field-aligned potential drops where perhaps none exist.

We have found that our previously reported method utilizing the similarity transformation provides a natural framework for such study. Given that the physical observations in such events are localized near the satellite, one really only knows the altitude-asymptotic form of the conic. Using the similarity transformation theory, the entire event can be reduced to two parameters, which are roughly analogous to an energy and pitch angle of the conic. The simultaneous observations of two *a priori* uncorrelated instruments, the EICS and PWI instruments of DE-1, may then be cast into this language for the purpose of comparison (Crew *et al.*, J. Geophys. Res., **94**, 1989, in press).

To highlight these results, we describe the comparisons of data and theory for the event centered around UT 74800 s on Day 81288 (Klumppar *et al.*, J. Geophys. Res., **89**, 10779, 1984). The conic distribution  $f_o(v_{\perp}, v_{\parallel})$  constructed from four spins of EICS data are shown in Fig. 13. Contours are placed at half decades, and the darker regions denote the greatest phase space density. From theoretical considerations, we note that such a conic may be characterized by parameters  $v_o$  and  $\sigma$  determined by straight forward moment calculations. Fig. 14 gives the time series of the values of these parameters based on the EICS data. In each panel, the dotted and dashed lines correspond to the right and left halves of the conic, and the solid points with error bars correspond to their average. Squares and triangles distinguish the two ways in which pairs of spins may be composed to construct a complete energy scan; these two ways are undifferentiated for the lines. Fig. 15 is a theoretical contour plot for values of  $v_o = 160$  km/s and  $\sigma = 8/3$  estimated from Fig. 14 to be those most representative of the conic event of Fig. 13. The resemblance of Fig. 13 to Fig. 15 is remarkable. In addition, we have compared these results with the PWI data for the same time period and found that the choice of the values of the parameters  $v_o$  and  $\sigma$  are consistent with the wave data as well. In particular the intensification of



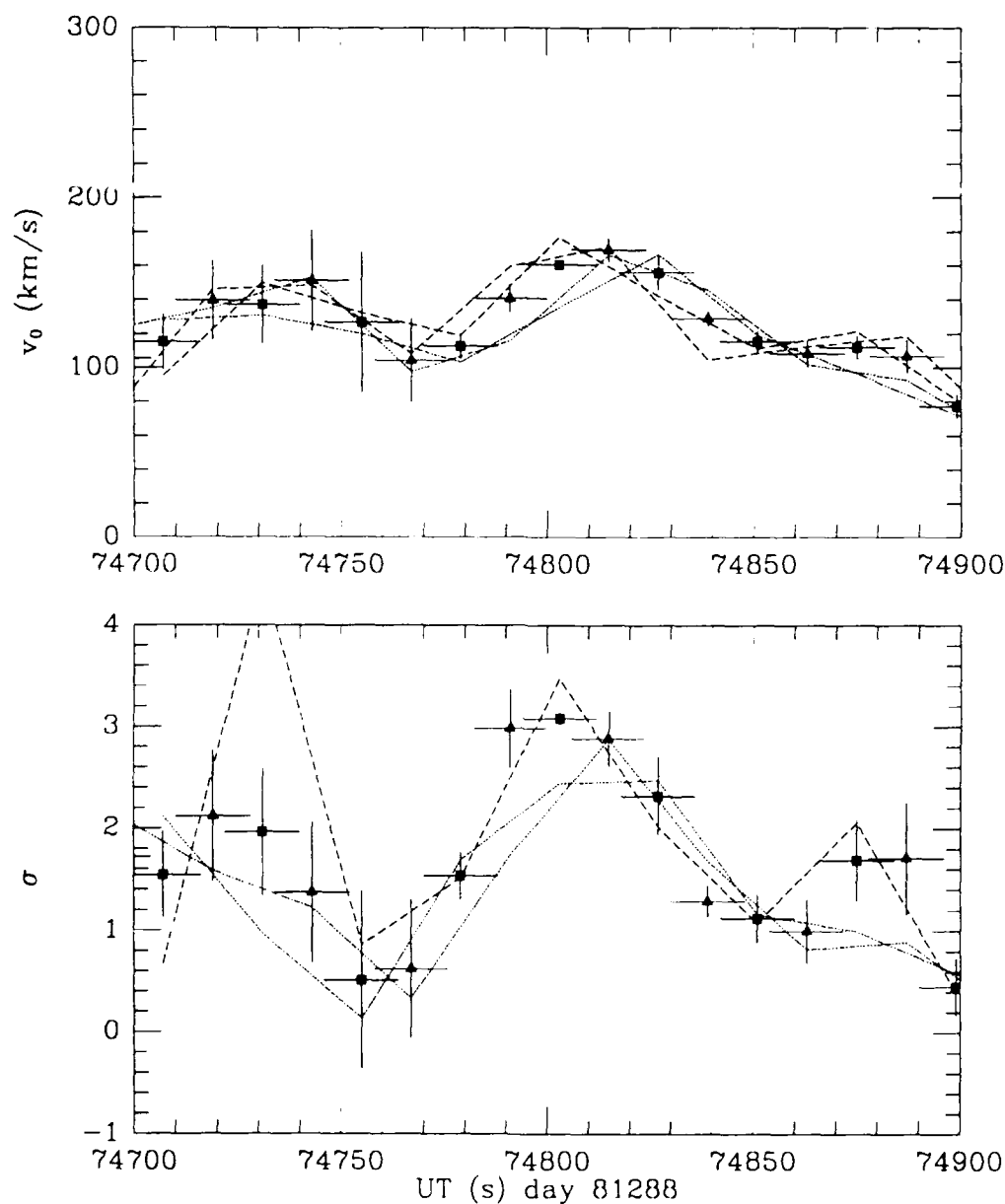


Figure 14. Time series of  $v_0$  and  $\sigma$  on day 81288 based on EICS observations. In each panel, the dotted and dashed lines correspond to the right and left halves of the conic, and the solid points with error bars correspond to their average. Squares and triangles distinguish the two ways in which pairs of spins may be composed to construct a complete energy scan; these two ways are undifferentiated for the lines.

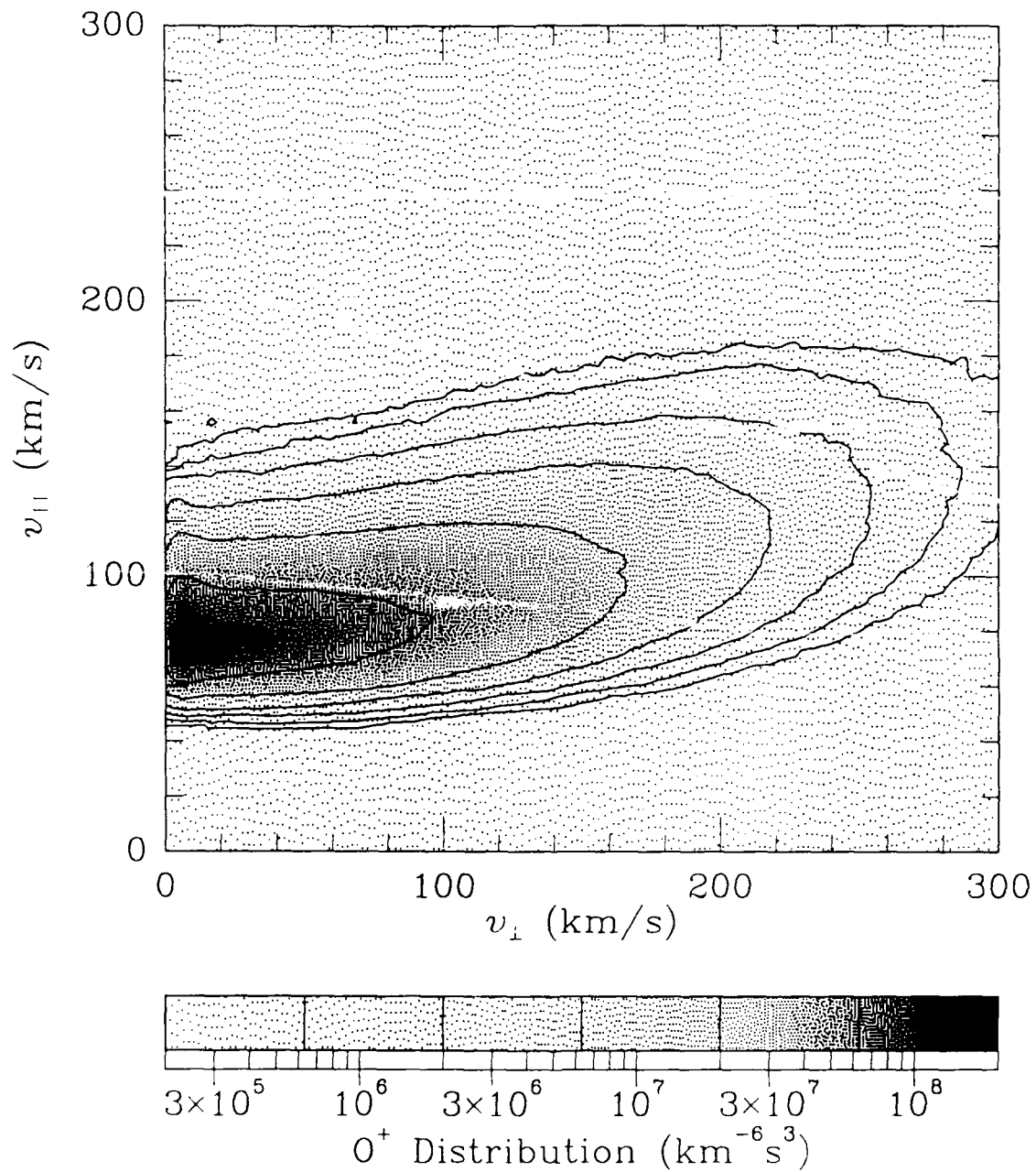


Figure 15. Conic distribution  $v_o$  constructed from  $F(x, y)$  with  $\sigma = 8/3$  and a velocity scale of  $v_o = 160$  km/s. The contour/halftone representation is identical to that of Figure 13.

the conic near 74800 s is directly attributable to a similar intensification of the wave activity as seen with the PWI instrument.

## 2. Low-altitude Transverse Ion Acceleration

The recent MARIE rocket campaign over Greenland (Yau *et al.*, J. Geophys. Res., **88**, 541, 1983), has provided probably the most complete and detailed set of observations within the regions of low-altitude (locally) accelerated ions available. Our theoretical calculations and plasma simulations of VLF waves provide a model for the ion acceleration processes occurring during the formation of conics near auroral arcs, as reported in these observations. We are able to carry out some quantitative and detailed comparisons of our model calculations with these observations. As a preliminary, we note the following traits of the observed particle acceleration as reported. From the *in situ* plasma and wave measurements, a strong correlation was found between the VLF wave intensity and the energetic ion flux; preferential acceleration of hydrogen relative to oxygen occurred; and enhancements of field-aligned electron fluxes were detected. The frequency spectrum of the VLF turbulence around the lower hybrid frequency showed structures spaced at the hydrogen gyrofrequency, suggesting that ion damping of the waves was responsible for the acceleration; the amplitude of the turbulence was several tens of mV/m, strong enough to account for the ion energies. Finally, the form of the ion velocity distribution had the high energy tails that are characteristic of the acceleration observed in numerical simulations. All of these features have been observed on other missions and satellites, but never as convincingly as observed here. In addition, there are provocative new observations of intense VLF wave packets of "lower hybrid spikelets" observed in conjunction with transversely accelerated ions. These are evidence of the collapse of lower hybrid solitons. We conducted a detailed quantitative analysis of the observed data against the ion conic formation model via lower hybrid turbulence.

We are collaborating with Professor P. M. Kintner of Cornell University, Dr. J. M. Retterer of the Air Force Geophysics Laboratory, and Dr. A. Yau of the Canadian National Research Council in these research activities.

### 3. *Counterstreaming Electrons*

Counterstreaming electrons were occasionally observed during ion acceleration events when lower hybrid turbulence was present. Such a peculiar type of electron population could arise from the interaction of the ambient electron population with the parametrically excited lower hybrid waves during the mode-coupling scattering process in the developmental stage of the VLF turbulence.

The exact details of how counterstreaming electrons are formed can be better understood in terms of our two-dimensional simulation of electron beam-generated VLF turbulence. We have evaluated the possibility that the observed counterstreaming electrons were generated by the VLF turbulence as suggested.

We are collaborating with Dr. J. M. Retterer of the Air Force Geophysics Laboratory, Dr. A. Yau of the Canadian Research Council, Dr. M. André of the Swedish Space Institute, Dr. H. Koskinen of the Finnish Meteorological Institute, Dr. J. D. Winningham of the Southwest Research Institute, Dr. W. K. Peterson of the Lockheed Palo Alto Research Laboratory, and Drs. D. A. Gurnett and R. L. Huff of the University of Iowa in this research.

#### IV. OTHER CENTER ACTIVITIES

##### IV.A. Annual MIT Symposia on the Physics of Space Plasmas

###### 1. *Brief History and Motivation*

Based on the premise that the Greater Boston-New England area had one of the world's greatest concentration of scientists and research groups active in the field of the Physics of Space Plasmas, and that a forum such as this would be of value for: cross fertilization, consolidation of their intellectual resources and periodic focusing of its potential on topical problems, an annual symposium was organized initially under the leadership of Tom Chang, Bruno Coppi and J. R. Jasperse. During the past several years, this symposium series has gained such popularity that each year it is attended by over one hundred thirty scientists and graduate students worldwide. Although the participation of the symposia has become international, it still claims an active participation of the researchers regionally, including those from the Air Force Geophysics Laboratory, Naval Research Laboratory, Goddard Space Flight Center, Harvard University, Dartmouth College, Boston University, Boston College and the University of New Hampshire.

Perhaps the most lasting and most valuable fruits of these meetings are the seminal discussions and follow-on collaborations they foster. A sampling of such results are listed below.

(i) *A new boundary layer method* for solving pitch-angle scattering of electrons on auroral field lines was inspired by data presented by J. Whalen of the Air Force Geophysics Laboratory and J. Sharber of the Southwest Research Institute.

(ii) *First reporting* of the unexpected high degree of order in the polar cap ionospheric convection for northward interplanetary magnetic field (IMF) conditions was given by H. Carlson of the Air Force Geophysics Laboratory. This work has stimulated our current theoretical study of sub-visual polar cap F-region arcs in collaboration with the experimental groups at the Air Force Geophysics Laboratory and the Southwest Research Institute.

(iii) *First results* of closed-form solutions of the Balescu-Lenard-Poisson equations for collisional plasmas were reported

by J. R. Jasperse of the Air Force Geophysics Laboratory. Discussions at the meeting motivated an extension of the theory to phenomena at low frequencies.

(iv) *A new theory of central plasma sheet oxygen conics* withing the diffuse auroral region resulted from data presented by J. D. Winningham of the Southwest Research Institute.

(v) *A new photoelectron model* in the polar wind was stimulated by a presentation of S. Olbert on a non-classical electron heat flux theory of the solar wind.

(vi) *As a result of a review talk of the equatorial spread-F theory* by S. Ossakow of the Naval Research Laboratory, B. Basu of the Air Force Geophysics Laboratory and B. Coppi of MIT realized the need for a treatment of the problem taking into account the curved geomagnetic field line. This was necessary theoretically in order to obtain a self-consistent calculation.

(vii) *A deep penetration of the high energy tail of the solar wind electrons (strahl)* into the magnetosphere was suggested by J. Scudder and D. Fairfield of the Goddard Space Flight Center. This could then be observed as part of the precipitating electron population in the polar cap. Because of the symposium interactions, D. Hardy and M. S. Gussenhoven of the Air Force Geophysics Laboratory have searched and detected the presence of these particles using instruments aboard the DMSP satellites.

Since 1987, we have inaugurated a prestigious Alfvén Lecture Series in conjunction with the annual symposia in honor of the Nobel Laureate Hannes Alfvén of the Royal Institute of Technology of Sweden. The series is now more popular than ever. It is our intention to continue this tradition of this premier symposium series at MIT.

## 2. Programs of the 1987, 1988 and 1989 Symposia

Brief descriptions of the symposia during the past three years are given below.

(i) *The 1987 MIT Symposium on the "Physics of Space Plasmas"* was held on January 9, 1987 in the Marlar Lounge on the MIT Campus. A total of approximately 150 scientists and students participated. Professor Hannes Alfvén (Nobel Laureate) delivered the opening lecture entitled the "Plasma Universe". Topics covered by other invited lecturers included the solar wind, the Swedish "Viking" scientific satellite program, auroral electric and magnetic fields, the Uranian magnetosphere, comet Halley, plasma collisional theory, and the theoretical interpretation of observed of ion acceleration events.

(ii) *The 1988 MIT Symposium on the "Physics of Space Plasmas"* was held on January 26, 1988 in the Edgerton Hall on the MIT campus, with the participation of at least 120 scientists and students. Topics discussed at the symposium included: Low altitude flux transfer events, auroral dynamics, turbulent flow in the auroral ionosphere, polar cap arcs, magnetoconvection on the surface of the sun, the solar wind in the distant heliosphere, the Jovian magnetosphere, ionospheric and magnetospheric plasmas. Dr. Roger Gendrin, a renowned space plasma physicist from CNET/CRPE/France delivered the annual Alfvén lecture, which concerned the energization and retention of ring current particles.

(iii) *The 1989 MIT Symposium on the "Physics of Space Plasmas"* was held on January 19, 1989 in the Marlar Lounge of the McNair Building on the MIT campus with approximately 130 participants. The 1989 Alfvén Lecturer was the internationally renowned space physicist, James Dungey, Professor Emeritus of the Imperial College of London. Professor Dungey popularized the concepts of magnetic reconnection and the open magnetosphere. His innovative concepts and research findings have had a profound influence on the direction of the contemporary space plasma physics. Other invited lectures included presentations on the theories of magnetic reconnection, boundary layers in space plasmas, photoelectrons in the polar wind, as well as discussions related to the forthcoming Neptune encounter by the Voyager spacecraft, and other planetary ionospheric and magnetospheric topics.

#### IV.B. Cambridge Workshops in Theoretical Geoplasma Physics

##### 1. *Brief Description and Motivation*

During the past twenty years, some very useful progress has been made in the understanding of the the nature and dynamics of the plasma domains of the terrestrial ionosphere and magnetosphere. However, only limited tutorial accounts of the subject are available in the published literature. Consequently, it becomes extremely difficult for beginning graduate students or researchers of related fields to become acquainted with the exciting research topics that are being investigated by the active researchers in geoplasma physics. The Cambridge Workshops were conceived to address such a need.

In addition to the workshops themselves, it is hoped that the proceedings of the tutorial and specialty lectures given at the workshops can serve as informal textbooks dealing with the particular research topics discussed at these gatherings. Since the themes of the workshops are devoted to current research topics in geoplasma physics, the content of the proceedings are expected to contain both tutorial and current research findings. It is hoped that such proceedings will serve the dual purpose of acquainting the novice with the research topics considered as well as identifying the difficulties that are being encountered and addressed at the frontiers of geoplasma research.

Since the inception of these workshops, they have become quite well known and very popular. We have received countless inquiries and favorable comments from colleagues and students worldwide. The workshop typically attracts between 130 to 150 participants internationally, including scientists from the Air Force Geophysics Laboratory and the Naval Research Laboratory, as well as a large number of graduate students (30 to 40) from many outstanding institutions.

In organizing these workshops, we have relied heavily on the assistance of our colleagues from the Air Force Geophysics Laboratory, the Utah State University, and the Naval Research Laboratory. For example, Drs. J. R. Jasperse, H. Carlson, S. Ossakow, and R. Schunk have all contributed significantly to the detailed arrangements of these workshops.



It is our intention to continue these unique workshops at MIT.

## 2. *Programs of the 1987, 1988, and 1989 Workshops*

Brief accounts of the 1987, 1988, and 1989 Workshops are given below.

(i) *The theme of the 1987 inaugural workshop*, held July 28–August 1, 1987, was devoted to the coupling processes that occur among the ionosphere, the magnetosphere and the solar wind. Professor George Siscoe of UCLA delivered five seminal lectures on the macroscopic aspects of such coupling processes. Professor Robert Lysak of the University of Minnesota gave a succinct account of the microscopic processes that are expected or observed to occur during the coupling processes, particularly between the ionosphere and magnetosphere. In addition to these two outstanding tutorial lectures, there were many excellent lectures on such subjects as double layers, substorm dynamics, ion beams, magnetic reconnection, polar wind and various other coupling related processes. A total of over 135 scientists and students from the US, England, Germany, Sweden participated including a large contingent from the Air Force Geophysics Laboratory. A proceedings of over three hundred pages is now in print.

(ii) *The second in the series, the 1988 Cambridge Workshop*, was organized and successfully held on June 13–17, 1988. The theme of the workshop was "Polar Cap Dynamics and High Latitude Ionospheric Turbulence". The number of registrants for the workshop again exceeded 130 and included over 30 graduate students from institutions and universities all over the world. A number of space scientists from the Air Force Geophysics Laboratory were among the 130 geoplasma physicists who gave lectures and participated in the workshop. Tutorial lectures were given by Professor Mike Kelley of the Cornell University, Dr. Joe Huba of the Naval Research Laboratory, Professors Robert Schunk and Bela Fejer of Utah State University, Drs. Herbert Carlson and Edward Weber of the Air Force Geophysics Laboratory, Dr. John Foster of the Haystack Observatory, Professor Tamas Gombosi of the University of Michigan, Dr. Roderick A. Heelis of the University of Texas, Dallas, and Professor Jean P. St. Maurice of the University of Western Ontario.

Following the format of the 1987 workshop, there were additional invited lectures and poster presentations. A proceedings of over five hundred pages is in press, with publication expected in November 1989.

(iii) *The theme of the 1989 Cambridge Workshop* was "Wave-Particle Interaction Phenomena in Geoplasmas". Subtopics considered were ion acceleration, electron acceleration, pitch-angle diffusion, VLF induced electron precipitation, diffusion in the ring current, plasma turbulence and particle acceleration in the ionosphere, bow shock, pick-up ions, lower hybrid and ion cyclotron waves, ion-beam interactions, double-layers along auroral field lines, particle-wave correlation measurements, stochastic heating and acceleration, polar cap and polar cusp phenomena, and various nonlinear geoplasma processes. Invited lecturers include Professor Mary Hudson of Dartmouth College, Professors R. Helliwell and U. Inan of Stanford University, Professors J. Winkler and R. Lysak of the University of Minnesota, Dr. G. B. Crew of MIT, Dr. J. M. Retterer of the Air Force Geophysics Laboratory and MIT, Drs. M. Ashour-Abdalla and P. Pritchett from UCLA, Professor C. Dum and Dr. R. Treuman of the Max-Planck Institute of Extraterrestrial Physics and MIT, Professor C. S. Wu and Dr. F. Skiff of the University of Maryland, Drs. D. Winske and P. Gary of the Los Alamos National Laboratory, Dr. R. Potellette of CNET/CRPE France, Drs. M. Temerin, I. Roth and R. Ergun of UC Berkeley, Dr. M. André from the Swedish Space Institute and MIT, Drs. W. Peterson and D. Klumpar of Lockheed Palo Alto Research Laboratory, Dr. H. Koskinen of the Finnish Meteorological Institute and MIT, Dr. A. Yau of the Canadian Research Council, Professor P. Kintner of Cornell University, Professor R. McWilliams of UC Irvine, Dr. E. Villalon of Northeastern University, Dr. H. Matsumoto from Kyoto University, and Dr. H. Okuda from the Princeton Plasma Physics Laboratory. The workshop was held during June 12-16, 1989. A proceedings is in preparation, with publication anticipated early in 1990.

#### IV.C. Interaction with MIT Haystack Observatory-Millstone Radar Facility

Recently, it has been discovered that the anomalous UHF radar echoes from the topside ionosphere could be interpreted as reflections from the strong enhancement of ion acoustic turbulence produced by the field-aligned currents. Such plasma enhancements require large electron to ion temperature ratios and relatively large field-aligned currents.

As it has been discussed previously, in the high-latitude ionosphere and in the suprauroral region, other plasma irregularities and turbulence also exist even for moderate  $T_e/T_i$  ratios and weak currents. For example, lower hybrid waves are generally detected during inverted-V events. These waves are probably generated by the keV electron beams produced by the field-aligned kilovolt potential drops. These waves in turn can transversely accelerate the ionospheric ions to keV energies which, in turn, can excite other secondary plasma waves. Alternatively, double layers have been detected in the suprauroral region by polar-orbiting satellites S3-3 and DE-1. As demonstrated above, such nonlinear structures can be generated by very weak field-aligned currents and do not require the electron temperature to be larger than the ion temperature.

In regions of strong field-aligned currents, electrostatic ion cyclotron waves can be excited. In addition, other waves such the electromagnetic ion cyclotron waves, hybrid ion modes, and ion Bernstein modes can also be excited in the suprauroral region and in the topside ionosphere.

All such structures return "hard target" radar echoes. *The ability to differentiate such false "hard targets" from the "real thing" is certainly of prime importance to the mission of the Air Force.*

The Haystack Observatory with the collaboration of our Center has recently received a contract through the Defense University Research Instrumentation Program (DURIP) via AFOSR to support a combined experimental/theoretical investigation of the aforementioned plasma effects in the high-latitude ionosphere. The planned enhancement of the Millstone radar capability will shed new insight to the various types

plasma turbulence signatures associated with the strong echoes of two simultaneously operated radars. To analyze the data observed from these unique radar observations and to interpret the analyzed data, the MIT Haystack and Geoplasma Groups plan to work cohesively as one unit.

Drs. J. Foster and J. Holt of the MIT Haystack Observatory are actively collaborating with our Center in these activities.

#### IV.D. Visiting Scientists Program

As mentioned in the Introduction, we have a very strong Visiting Scientists Program. The following is a list of some of our visitors together with a brief description of some of their activities:

(i) *Dr. J. R. Jasperse, Air Force Geophysics Laboratory.* There is active and constant collaboration between Dr. Jasperse and members of the Center of Theoretical Geoplasma Physics. Joint research activities included the theory of plasma instability and turbulence, particle acceleration mechanisms, and diffusion and transport phenomena in the ionosphere. Dr. Jasperse has also participated in the joint planning of the MIT Symposia on the "Physics of Space Plasmas" and the Cambridge Workshops in Theoretical Geoplasma Physics.

(ii) *Dr. David Stern, NASA Goddard Space Flight Center.* Dr. Stern visited us during the spring semester of the 1987-88 academic year and gave a series of lectures on the history and theory of the global morphology of the ionosphere and magnetosphere. He also conducted numerous informal discussions with the members of the Center.

(iii) *Dr. Liu Chen, Plasma Physics Laboratory, Princeton University.* Dr. Chen visited us and discussed with us about plasma maser instabilities, low frequency MHD turbulence in the magnetosphere. He also gave a seminar on the ring current induced ULF waves.

(iv) *Dr. Mats André, Swedish Space Institute.* Dr. André has joined us for extended periods in research activities related to the data collected by the Viking satellite. Applying some of the theories developed at the Center, Dr. André was able to correlate the wave and ionospheric particle data collected near the polar cusp region of the magnetosphere.

Two papers related to this subject were published by Dr. André and his coworkers.

(v) *Dr. D. Vvedensky, Imperial College.* Dr. Vvedensky visited us several times to discuss with us our recently developed theory of "path integral formulation of ion conics heating". His insight on the theory of functional integration has been most enlightening.

(vi) *Dr. J. D. Winningham, Southwest Research Institute.* Dr. Winningham collaborated with us on several interesting research topics related to data collected by the DE-2 satellite: polar wind photoelectrons, cusp ions, flux transfer events, and plasma turbulence induced by intense velocity shears in the high-latitude ionosphere.

(vii) *Dr. J. M. Retterer, Air Force Geophysics Laboratory.* Dr. Retterer has been an integral part of our Center activities. He has collaborated with us in a number of research activities: ion heating, plasma turbulence in the inhomogeneous geoplasma environment, nonclassical polar wind, pitch angle diffusion, plasma simulations, and Monte Carlo calculations.

(viii) *Dr. C. Z. Cheng, Plasma Physics Laboratory, Princeton University.* Dr. Cheng joined us in discussing the phenomenon of mode coupling, mode conversion, and low frequency waves. He also gave a seminar on low frequency turbulence.

(ix) *Dr. C. Dum, Max-Planck Institute for Extraterrestrial Physics.* Dr. C. Dum worked with us on plasma turbulence and wave-particle interactions in the high-latitude ionosphere and associated phenomenon of beam-plasma interactions. One research paper resulting from these interactions has been accepted for publication by the Journal for Geophysical Research.

(x) *Dr. M. Heinemann, Air Force Geophysics Laboratory.* Dr. Heinemann is taking a year's leave of absence (1988-89) to work at our Center (while supported by AFOSR) and is working with Professor Olbert on MHD problems related to the geoplasma environment.

(xi) *Dr. Sunanda Basu, Emmanuel College/Air Force Geophysics Laboratory.* Dr. Sunanda Basu, whose recent research intersects nicely with our current study of ionospheric turbulence and ion acceleration, is

planning to join us as a Visiting Scientist for a full calendar year. Her presence at our Center will provide the same type of fruitful theory-experiment interactions which we have enjoyed with Dr. J. D. Winningham from the Southwest research Institute and Dr. Mats André of the Swedish Space Institute as described above.

(xii) *Dr. W. K. Peterson, Lockheed Palo Alto Research Laboratory.* Dr. Peterson has worked extensively with us on our recent work which explains the occurrence of a class of ion conic distributions via interaction with low frequency electromagnetic turbulence. In the process we have forged a model interaction between theorist and experimentalist with a synergism that produces significant results.

(xiii) *Dr. Hannu Koskinen, Finnish Meteorological Institute.* Dr. Koskinen visited us on a number of occasions. He has interacted with us on the parametric theory of lower hybrid waves, and the Viking observations of weak double layers along the auroral field lines.

(xiv) *Dr. Ilan Roth, University of California, Berkeley.* Dr. Roth has interacted with us on a number of research topics, particularly on Monte Carlo calculations of ion acceleration by electromagnetic plasma turbulence.

(xv) *Dr. Rachelle Bergmann, Rice University.* Dr. Bergmann, whose research in ion beam instabilities intersects with our own work on particle acceleration along auroral field lines, is planning to spend the coming summer with us as a visiting scientist. We plan to look at some of the analyzed data on ion beams as detected by the Dynamics Explorer 1 satellite with Dr. Peterson of the Lockheed Palo Alto Research Laboratory.

(xvi) *Dr. Andrew Yau, Herzberg Institute, National Research Council, Canada.* Dr. Yau has provided us with valuable experimental information on the transverse acceleration process in the lower ionosphere via particle data obtained by the MARIE rocket campaign. Recently we have joined Dr. Yau as a co-investigator for a proposal to NASA for a small-class explorer program called CATHIE (Canadian Auroral Topside High-resolution Ionospheric Explorer). The mission of CATHIE will be to investigate: transverse ionospheric ion acceleration, discrete nonlinear plasma structure, plasma turbulence, and small-scale magnetic field

structure and ionospheric currents.

(xvii) *Professor Paul Kintner, Cornell University.* Professor Kintner has a long history of interaction with our Center. Our theoretical investigation of transverse ion acceleration by lower hybrid waves was motivated by his data from the S3-3 satellite. We have collaborated on research involving data collected by the PORCUPINE and MARIE rocket experiments. We serve as a theoretical consultant to Professor Kintner on the Focus electric field experiment which is to be flown on the proposed CATHIE explorer.

(xviii) *Professor Hannes Alfvén, Swedish Royal Institute of Technology.* As a champion of Space Plasma Physics, Professor Alfvén embraces our center with open arms. He served as a consultant and gave a lecture on the "Plasma Universe" during the 1987 MIT Symposium on the Physics of Space Plasmas. He is the sponsor of the annual Alfvén lecture series.

#### **IV.E. Informal Geoplasma Seminar Series**

We have organized a popular Informal Geoplasma Seminar series for the MIT-Greater Boston community. The topics of the seminars have varied from low to high frequency plasma waves, from the ionosphere to the magnetosphere, and from theoretical investigations to experimental discoveries. Faculty, staff, and graduate students from the Center for Space Research, the Physics Department, the Plasma Fusion Center, the Electrical Engineering Department, the Department of Aeronautics and Astronautics, Harvard-Smithsonian Center for Astrophysics, the Department of Earth and Planetary Sciences, the Haystack Observatory, Boston University, Boston College, and the Air Force Geophysics Laboratory have participated in this active intellectual endeavor.

**V. PROFESSIONAL PERSONNEL ASSOCIATED WITH THE PROGRAM**

Tom T. S. Chang, Director

Geoffrey B. Crew, Assistant to the Director and Research Scientist

John Belcher, Professor

Stanislaw Olbert, Professor Emeritus

Daniel Hastings, Associate Professor

(Affiliation through a Lockheed grant)

David Tetreault, Research Scientist

Peter Yoon, Postdoctoral Scientist

Fareed Yaseen, Postdoctoral Scientist

John R. Jasperse, Research Affiliate

(without remuneration)

Hannes Alfvén (Nobel Laureate), Sponsor of Alfvén Lecture Series

John M. Retterer, Research Affiliate

(without remuneration)

Christian T. Dum, Visiting Scientist

Michael Heinemann, Visiting Scientist

M. André, Visiting Scientist

J. David Winningham, Visiting Scientist

Hannu Koskinen, Visiting Scientist

Rachelle Bergmann, Visiting Scientist

Jay Johnson, Graduate Student and Research Assistant

Wing Yee Sunny Tam, Graduate Student and Research Assistant

Hang Hu, Graduate Student and Research Assistant

(affiliation through a Haystack research grant)

Nicholas Gatsonis, Graduate Student and Research Assistant

(affiliation through a Lockheed grant)

Kenton C. Phillips, CSR Computer Manager

Mary F. Jeanig, Senior Secretary

Dr. Tom Chang serves as Principal Investigator/Program Director of the Center. He was responsible for the initiation of the current geoplasma program at MIT. He is a Fellow of the American Physical Society and holder of two doctoral degrees in theoretical physics and engineering, was an editor of the international journal *Plasma Physics*, has done postdoctoral research at the University of Cambridge, and was an



honorary research fellow at the Lyman Laboratory of Physics at Harvard University. He enjoys an international reputation in space plasma research, strong turbulence and stochastic theories and has previously directed a center of excellence activity under the sponsorship of the National Science Foundation.

Dr. Chang is assisted by Dr. G. B. Crew, a theorist with 12 years' experience in a broad range of plasma physics disciplines, and a former National Science Foundation Graduate Fellow. He has done outstanding research in particle acceleration, wave propagation and mode conversion processes, plasma instability and magnetic reconnection processes, and comparison of theory with actual space plasma data. Dr. Crew also oversees the computer facilities at the center.

Professor John Belcher is the principal investigator of the Voyager program at MIT. His affiliation with the Center has provided highly beneficial interactions involving the MHD description of magnetospheric and ionospheric processes, and in particular, Alfvén wave interactions in space plasmas. Professor S. Olbert, though retired, continues to interact with the Center on research topics involving anisotropic electron distributions along open magnetic field lines and plasma radiations due to the conducting objects in the lower ionosphere. Professors Belcher and Olbert have extensive knowledge and experience in plasma processes of other planetary magnetospheres. Their experiences proved extremely useful for comparative analysis with the Earth's magnetosphere and ionosphere. Professor D. Hastings is affiliated with the Center through a Lockheed basic research grant. Together with Professor Olbert, they have collaborated on plasma radiations induced by moving objects in the lower ionosphere.

## VI. CHRONOLOGICAL LISTING OF RECENT PAPERS AND BOOKS

## VI.A. Papers

- [1] G. B. Crew, Tom Chang, J. M. Retterer, W. K. Peterson, D. A. Gurnett, and R. L. Huff, "Ion cyclotron resonance heated conics: theory and observations", *J. Geophys. Res.*, **94** (1989), in press.
- [2] Jay R. Johnson, Tom Chang, G. B. Crew, and Mats André, "Equatorially generated ULF waves as a source for the turbulence associated with ion conics", *Geophys. Res. Lett.*, **16** (1989), in press.
- [3] C. T. Dum, "Simulation studies of plasma waves in the electron foreshock: The generation of Langmuir waves by gentle bump-on-tail", *J. Geophys. Res.* (1989), submitted.
- [4] C. T. Dum and Y. Serizawa, "Nonlocal analysis of finite beam-driven instabilities", *Phys. Fluids* (1989), submitted.
- [5] C. T. Dum and L. Muschietti, "Current-driven ion cyclotron turbulence—Evolution of the electron distribution and wave spectrum", *J. Geophys. Res.*, **94** (1989), in press.
- [6] F. Yasseen, J. M. Retterer, Tom Chang, and J. D. Winningham, "Monte-Carlo Modeling of Polar Wind Electron Distributions with Anomalous Heat Flux", *Geophys. Res. Lett.*, **16**, p. 1023 (1989).
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#### VI.B. Books

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- [2] Tom Chang, G. B. Crew, and J. R. Jasperse (eds.), *Physics of Space Plasmas (1988)*, SPI Conference Proceedings and Reprint Series, No. 8 (Scientific Publishers, Inc., Cambridge, MA, 1989), in press.
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- [5] Tom Chang, M.K. Hudson, J.R. Jasperse, R.G. Johnson, P.M. Kintner, M. Schulz, and G.B. Crew (eds.), *Ion Acceleration in the Magnetosphere and Ionosphere*, Geophysical Monograph Series, Vol. 38 (American Geophysical Union, Washington, D.C., 1986).

#### VII. CHRONOLOGICAL LISTING OF RECENT PAPERS PRESENTED

- [1] AGU Fall Meeting in San Francisco, CA, Dec. 1989, G.B. Crew, W.K. Peterson, and H.L. Collin, "Implications of energy conservation for auroral ion beams".
- [2] AGU Fall Meeting in San Francisco, CA, Dec. 1989, F. Yasseen, J.M. Retterer, and T. Chang, "Kinetic collisional model of the polar wind electron distribution".
- [3] AGU Fall Meeting in San Francisco, CA, Dec. 1989, J.R. Johnson, T. Chang, G.B. Crew, and M. Andre, "Equatorially generated ULF waves as a source for the turbulence associated with ion conics".
- [4] 31st Annual Meeting of the Division of Plasma Physics in Anaheim, CA, Nov. 1989, G.B. Crew, M. Andre, and W.K. Peterson, "Ion cyclotron resonance heating in the cusp/cleft".
- [5] 31st Annual Meeting of the Division of Plasma Physics in Anaheim, CA, Nov. 1989, F. Yasseen, J.M. Retterer, and T. Chang, "Effect of anomalous photoelectron heat fluxes on the polar wind electric field".
- [6] 1989 IAGA Assembly in Exeter, UK, July-August, 1989, J.R. Johnson, T. Chang, G.B. Crew, and M. Andre, G.B. Crew, and T. Chang, "Ion cyclotron resonance heated conics".
- [7] 1989 Cambridge Workshop in Theoretical Geoplasma Physics in Cambridge, MA, June, 1989, G.B. Crew and T. Chang, "Particle acceleration by electromagnetic ion cyclotron turbulence".

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- [9] 1989 Cambridge Workshop in Theoretical Geoplasma Physics in Cambridge, MA, June, 1989, C.T. Dum, "The electron beam instability and turbulence".
- [10] 1989 Cambridge Workshop in Theoretical Geoplasma Physics in Cambridge, MA, June, 1989, D. Tetreault, "3D model of double layers/EIC waves in the auroral acceleration region".
- [11] 1989 MIT Symposium on the Physics of Space Plasmas, D. Tetreault, "Turbulent Reconnection in Plasmas".
- [12] International Union on Radio Science, 1988 National Meeting, T. Chang, "Electromagnetic Tornadoes in Space".
- [13] Eringen Symposium, Society of Engineering Science, 1988 25th Anniversary Meeting, T. Chang, "Electromagnetic Tornadoes in Earth's Magnetosphere and Ionosphere".
- [14] American Geophysical Union, 1988 Fall Meeting, J.M. Retterer, J.R. Jasperse, and D. Decker, "A Kinetic Model for the Diffuse Aurora".
- [15] American Geophysical Union, 1988 Fall Meeting, F. Yasseen, J.M. Retterer, and T. Chang, "Monte-Carlo Modeling of Polar Wind Electron Distributions with Anomalous Heat Flux".
- [16] American Geophysical Union, 1988 Fall Meeting, G.B. Crew, T. Chang, J.M. Retterer, W.K. Peterson, D.A. Gurnett, and R.L. Huff, "Ion conics: detailed comparison of theory and observations".
- [17] American Geophysical Union, 1988 Fall Meeting, W.K. Peterson, M. André, G.B. Crew, A.M. Persoon, M. Engebretson, and C. Pollock, "Heating of thermal oxygen ions near the equatorward boundary of the mid-altitude polar cusp: Dynamics Explorer observations".
- [18] American Geophysical Union, 1988 Fall Meeting, J.R. Johnson, Tom Chang, and G.B. Crew, "Mode conversion of low frequency waves in a multispecies plasma".



- [19] American Physical Society, 1988 Fall Meeting of the Division of Plasma Physics, F. Yasseen, J.M. Retterer, and T. Chang, "Monte-Carlo Modeling of Polar Wind Electron Distributions with Anomalous Heat Flux".
- [20] American Physical Society, 1988 Fall Meeting of the Division of Plasma Physics, G.B. Crew and T. Chang, "Particle Heating via the Path Integral".
- [21] American Physical Society, 1988 Fall Meeting of the Division of Plasma Physics, P. Yoon and T. Chang, "Exact Dielectric Tensor for Relativistic Magnetized Anisotropic Plasmas".
- [22] American Physical Society, 1988 Fall Meeting of the Division of Plasma Physics, J.R. Johnson, G.B. Crew, and T. Chang, "Mode Conversion of Low Frequency Waves in Multispecies Plasmas".
- [23] American Physical Society Topical Conference on Plasma Astrophysics, October 1988, T. Chang, "Global Kinetic Theory of Astrophysical Jets".
- [24] NATO Advanced Research Workshop on Electromagnetic Coupling in the Polar Clefts and Caps, September 1988, W.K. Peterson, M. André, G.B. Crew, A.M. Persoon, M. Engebretson, and C. Pollock, "Heating of Thermal Oxygen Ions near the Equatorward Boundary of the Mid-Altitude Polar Cusp: Dynamics Explorer observations".
- [25] Joint Varenna-Abastumani Workshop of Plasma Astrophysics, Summer 1988, T. Chang, "Oblique Whistlers: Their Relevance to Nonthermal Coupling of Ions and Electrons in Accretion Flow and Supercritical Quasi-Perpendicular Collisionless Shocks".
- [26] Joint Varenna-Abastumani Workshop of Plasma Astrophysics, Summer 1988, T. Chang, "Global Kinetic Theory of Astrophysical Jets".
- [27] International Conference on Auroral Physics, Dedicated to the Centenary of the Birth of Sydney Chapman (Cambridge, UK), July 1988, J.M. Retterer, T. Chang, and J.R. Jasperse, "Plasma Simulation of Intense VLF Turbulence and Particle Heating in the Supraauroral Region".

- [28] 1988 Cambridge Workshop in Theoretical Geoplasma Physics: Polar Cap Dynamics and High Latitude Ionospheric Turbulence, J.M. Retterer, T. Chang, and J.R. Jasperse, "Plasma Simulation of Intense VLF Turbulence and Particle Heating in the Supraauroral Region".
- [29] 1988 Cambridge Workshop in Theoretical Geoplasma Physics: Polar Cap Dynamics and High Latitude Ionospheric Turbulence, T. Chang, "Kinetic Global Collisional Model of Anisotropic Electrons Along Polar Cap Field Lines".
- [30] 1988 MIT Symposium on the Physics of Space Plasmas, D. Winningham, "Low Altitude Flux Transfer Events".
- [31] American Astronomical Society, 1988 Winter Meeting, T. Chang, "Plasma Maser and Gravitational Drift Instability Theory of Radio Jets".
- [32] American Geophysical Union, 1987 Fall Meeting, T. Chang and G.B. Crew, "Path Integral Formulation of Ion Conics".
- [33] American Geophysical Union, 1987 Fall Meeting, J.M. Retterer, T. Chang, and J.R. Jasperse, "Two-D Simulation of Ion and Electron Acceleration by VLF Turbulence in the Supraauroral Region".
- [34] American Geophysical Union, 1987 Fall Meeting, G.B. Crew, T. Chang, J.M. Retterer, W.K. Peterson, D.A. Gurnett, and R.L. Huff, "Ion Conics: Detailed Comparison of Theory and Observations".
- [35] American Geophysical Union, 1987 Fall Meeting, M. André, G.B. Crew, H. Koskinen, L. Matson, and J.M. Retterer, "Transverse Ion Heating in the Cusp Region".
- [36] Chapman Conference on Plasma Waves and Instabilities in Magnetospheres and at Comets (Sendai, Japan), M. André, H. Koskinen, and L. Matson, "Simultaneous Observations of Ion Waves and Ion Conics in and Near The Polar Cusp".
- [37] American Physical Society, 1987 Fall Meeting of the Division of Plasma Physics, D. Tetreault, "MHD Clump Instability".
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Formulation of Ion Conic Formation".

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- [40] Third International School on Space Simulations, June 1987, T. Chang, G.B. Crew, and J.M. Retterer, "Simulation and Theory of Heavy Ion Acceleration".
- [41] Third International School on Space Simulations, June 1987, G.B. Crew, T. Chang, and J.M. Retterer, "Simulation of Oxygen Conic Formation".
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- [49] 1987 MIT Symposium on the Physics of Space Plasmas, T. Chang, "Gyroresonance Heating of Central Plasma Sheet  $O^+$  Conics by Left-Hand Polarized Waves".

- [50] 1987 MIT Symposium on the Physics of Space Plasmas, J.R. Jasperse and B. Basu, "Solutions of the Linearized Balescu-Lenard-Poisson Equations for a Weakly-Collisional Plasma: Some New Results".
- [51] American Geophysical Union, 1986 Fall Meeting, G.B. Crew and Tom Chang, "Similarity Model of Ion Conic Formation".
- [52] American Geophysical Union, 1986 Fall Meeting, J.M. Retterer, T. Chang, G.B. Crew, J.R. Jasperse, and J.D. Winningham, "Ion Conics: Case Study of Two Accelerations Mechanisms".
- [53] American Physical Society, 1986 Fall Meeting of the Division of Plasma Physics, T. Chang, "Ion Acceleration in the Magnetosphere by Broad Band Lower Hybrid Waves and Electromagnetic Turbulence in the Ion Cyclotron Range of Frequencies".
- [54] American Physical Society, 1986 Fall Meeting of the Division of Plasma Physics, T. Chang, G.B. Crew, N. Hershkowitz, J.R. Jasperse, J.M. Retterer, and J.D. Winningham, "Modeling of  $O^+$  Conics in the Magnetospheres".
- [55] Huntsville Workshop on Magnetosphere-Ionosphere Plasma Models, October 1986, J.M. Retterer, G.B. Crew, T. Chang, and J.R. Jasperse, "Monte Carlo Modeling of Oxygen Ion Acceleration by Broadband Electromagnetic Ion Cyclotron Resonance".
- [56] Huntsville Workshop on Magnetosphere-Ionosphere Plasma Models, October 1986, G.B. Crew and T. Chang, "Kinetic Treatment of Oxygen Conic Formation in the Central Plasma Sheet by Broadband Waves".
- [57] Huntsville Workshop on Magnetosphere-Ionosphere Plasma Models, October 1986, T. Chang, G.B. Crew, N. Hershkowitz, J.R. Jasperse, J.M. Retterer, and J.D. Winningham, "Modeling of  $O^+$  Conics in the Central Plasma Sheet".
- [58] American Geophysical Union, 1986 Spring Meeting, G.B. Crew and T. Chang, "Kinetic Treatment of Oxygen Conic Formation in the Central Plasma Sheet by Broadband Alfvén Waves".

- [59] American Geophysical Union, 1986 Spring Meeting, Tom Chang, G.B. Crew, N. Hershkowitz, J.R. Jasperse, J.M. Retterer, and J.D. Winningham, "Transverse Acceleration of Oxygen Ions by Electromagnetic Ion Cyclotron Resonance With Broad Band Alfvén waves".
- [60] American Geophysical Union, 1986 Spring Meeting, J.M. Retterer, G.B. Crew, Tom Chang, and J.R. Jasperse, "Monte Carlo modeling of oxygen ion acceleration by broadband electromagnetic ion cyclotron resonance".

**VIII. EPILOG**

A renewal proposal for the continuation of support for the Center was submitted to AFOSR in April 1989 and has received initial approval. Thus in the future activities of the Center, we shall

- A. Continue the development of a theoretical Center in Geoplasma Physics which was established in 1986 by an initial AFOSR-URI contract.
- B. Conduct an annual MIT Symposium series on the "Physics of Space Plasmas".
- C. Conduct an annual Cambridge Workshop series in "Theoretical Geoplasma Research".
- D. Provide opportunities for the exchange of scientific personnel between MIT, AFGL and other research organizations.
- E. Continue to provide opportunities for graduate student education in geoplasma physics.
- F. Investigate the phenomenon of ionosphere-magnetosphere coupling.
- G. Study sub-visual F-region polar cap arcs and other auroral phenomena produced by local velocity shears.
- H. Study the three-dimensional effects of weak double layers along auroral field lines.
- I. Study the transverse acceleration and ion heating in the lower ionosphere.

- J. Conduct particle simulations of high-latitude lower hybrid turbulence and charged particle acceleration.
- K. Study the effects of inhomogeneities on plasma turbulence in the auroral zone and the associated mode-conversion phenomenon.
- L. Conduct a self-consistent theoretical analysis of the polar wind photoelectrons.
- M. Study the flux transfer and diffusion effects and turbulent magnetic reconnection.
- N. Conduct detailed comparison of developed theories with experimental data obtained by rockets and satellites.
- O. Study current-driven instabilities and plasma turbulence in the auroral zone and compare the results with incoherent radar observations.
- P. Study the effect of finite current sheet geometry on current-driven instabilities and nonlinear plasma wave saturation mechanisms.
- Q. Provide technical inputs to scientists affiliated with the Air Force Geophysical Laboratory for the ultimate application of developed theories to the various support programs that are relevant to the missions of the Air Force.